BOEING

NAS-15196
DRL T-1346
DRD MA - 664T
LINE ITEM 3

CR-151557

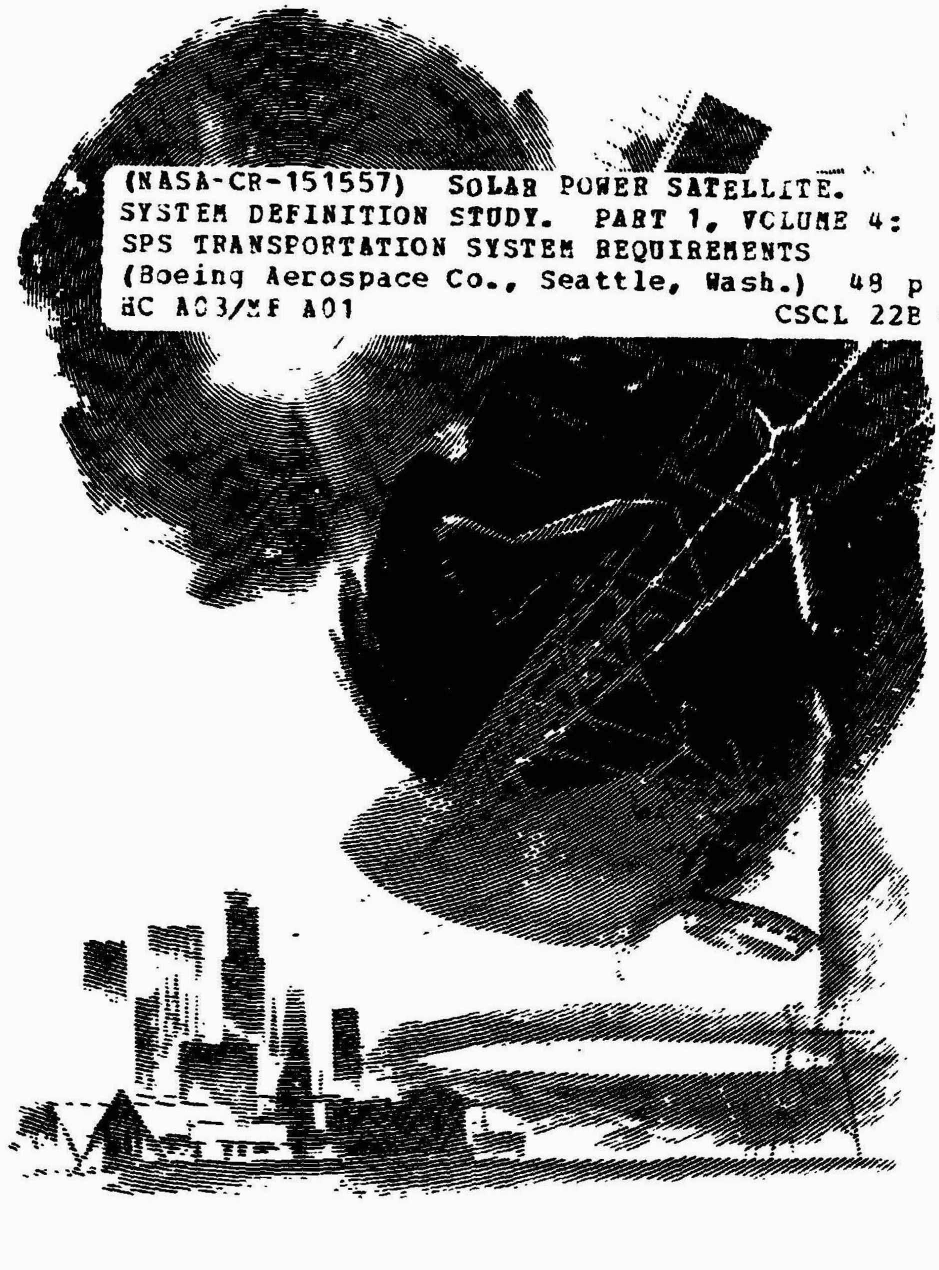
D180-20689-4
Part 1 Volume IV

SPS Transportation System Requirements

(NASA-CR-151557) SOLAR POWER SATELLITE. SYSTEM DEFINITION STUDY. PART 1, VOLUME 4: SPS TRANSPORTATION SYSTEM REQUIREMENTS (Boeing Aerospace Co., Seattle, Wash.) 48 p HC A03/MF A01 CSCL 22B G3/15

N78-13102

Unclas
53640



Solar Power Satellite

SYSTEM DEFINITION STUDY

D180-20689-4

Contract NAS9-15196
DRL Number T-1346
DRD Number MA-664T
Line Item 3

Solar Power Satellite
SYSTEM DEFINITION STUDY

Part 1 Volume IV

SPS Transportation System Requirements

August 1, 1977

Submitted to
The National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
In Partial Fulfillment of the Requirements
of Contract NAS 9-15196

Approved By: G.R. Woodcock
G.R. Woodcock
Study Manager

Boeing Aerospace Company
Missiles And Space Group
Space Division
P.O. Box 3999
Seattle, Washington

FOREWORD

The SPS systems definition study was initiated in December 1976. Part I was completed on May 1, 1977. Part I included a principal analysis effort to evaluate SPS energy conversion options and space construction locations. A transportation add-on task provided for further analysis of transportation options, operations, and costs.

The study was managed by the Lyndon B. Johnson Space Center (JSC) of the National Aeronautics and Space Administration (NASA). The Contracting Officer's Representative (COR) was Clarke Covington of JSC. JSC study management team members included:

Lou Livingston	System Engineering and Analysis	Dick Kennedy	Power Distribution
Lyle Jenkins	Space Construction	Bob Ried	Structure and Thermal Analysis
Jim Jones	Design	Fred Stebbins	Structural Analysis
Sam Nassiff	Construction Base	Bob Bond	Man-Machine Interface
Buddy Heineman	Mass Properties	Bob Gundersen	Man-Machine Interface
Dickey Arndt	Microwave System Analysis	Hu Davis	Transportation Systems
R. H. Dietz	Microwave Transmitter and Rectenna	Harold Benson	Cost Analysis
Lou Leopold	Microwave Generators	Stu Nachtwey	Microwave Biological Effects
Jack Seyl	Phase Control	Andrei Konradi	Space Radiation Environment
Bill Dusenbury	Energy Conversion	Alva Hardy	Radiation Shielding
Jim Cioni	Photovoltaic Systems	Don Kessler	Collision Probability
Bill Simon	Thermal Cycle Systems		

The Boeing study manager was Gordon Woodcock. Boeing technical leaders were:

Vince Caluori	Photovoltaic SPS's	Jack Gewin	Power Distribution
Dan Gregory	Thermal Engine SPS's	Don Grim	Electric Propulsion
Eldon Davis	Construction and Orbit-to-Orbit Transportation	Henry Hillbrath	Propulsion
Hal DiRamio	Earth-to-Orbit Transportation	Dr. Ted Kramer	Thermal Analysis and Optics
Dr. Joe Gauger	Cost	Keith Miller	Human Factors and Construction Operations
Bob Conrad	Mass Properties	Jack Olson	Configuration Design
Rod Darrow	Operations	Dr. Henry Oman	Photovoltaics
Bill Emsley	Flight Control	John Perry	Structures

The Part I Report includes a total of five volumes:

Vol. I	D180-20689-1	Executive Summary
Vol. II	D180-20689-2	System Requirements and Energy Conversion Options
Vol. III	D180-20689-3	Construction, Transportation and Cost Analyses
Vol. IV	D180-20689-4	SPS Transportation System Requirements
Vol. V	D180-20689-5	SPS Transportation: Representative System Descriptions

Requests for information should be directed to Gordon R. Woodcock of the Boeing Aerospace Company in Seattle or Clarke Covington of the Spacecraft Design Division of the Johnson Space Center in Houston.

TABLE OF CONTENTS

TABLE OF CONTENTS

VOLUME IV
TRANSPORTATION SYSTEM REQUIREMENTS

1.0 INTRODUCTION

Applicable results of the SPS transportation studies funded by the transportation add-on effort were distilled into a best-estimate set of transportation system requirements. These are presented in this document in specification-like statements. Each statement or related group of statements is followed by a rationale statement explaining the reason or source of the requirement.

The requirement effort has avoided configuration assumptions wherever possible. Cases where a requirement applies to a specific assumption are so annotated.

2.0 CARGO LAUNCH VEHICLE REQUIREMENTS

Requirement
Cargo launch vehicles are intended to provide the means to transport SPS hardware, orbit transfer propellant and any other appropriate freight from the Earth launch site to a low Earth orbit destination. They are not intended as crew transporters. They need not be manned; they may be manned if this aids meeting the requirements set forth below and if it does not expose flight crews to unnecessary risks.

The overriding design goal for the SPS cargo vehicle (HLLV's) is to minimize the recurring cost per unit mass. Also important are large (Saturn V class or greater) payload mass lift and volume capabilities. Very high total traffic rates, by comparison to historical experience or Shuttle traffic model estimates, are projected for an SPS program.

Rationale
The total transportation mass/volume requirements for SPS cargo and crew requirements are widely disparate as indicated by Figure 2-1. Therefore, the cargo transportation system should not be burdened by unique requirements deriving from the crew transportation function.

Transportation cost is a major factor in total SPS costs. Even if minimized to the greatest degree presently considered practical, transportation costs represent roughly 40% of total SPS capital costs.

2.1 Mission Profiles and Operations

2.1.1 Launch Site

Requirement
The design reference launch site shall be the NASA Kennedy Space Center on the east coast of Florida. Alternative launch sites are not precluded and may be considered as design reference in those instances where features of particular configurations make it necessary (e.g., need for an available down-range landing site).

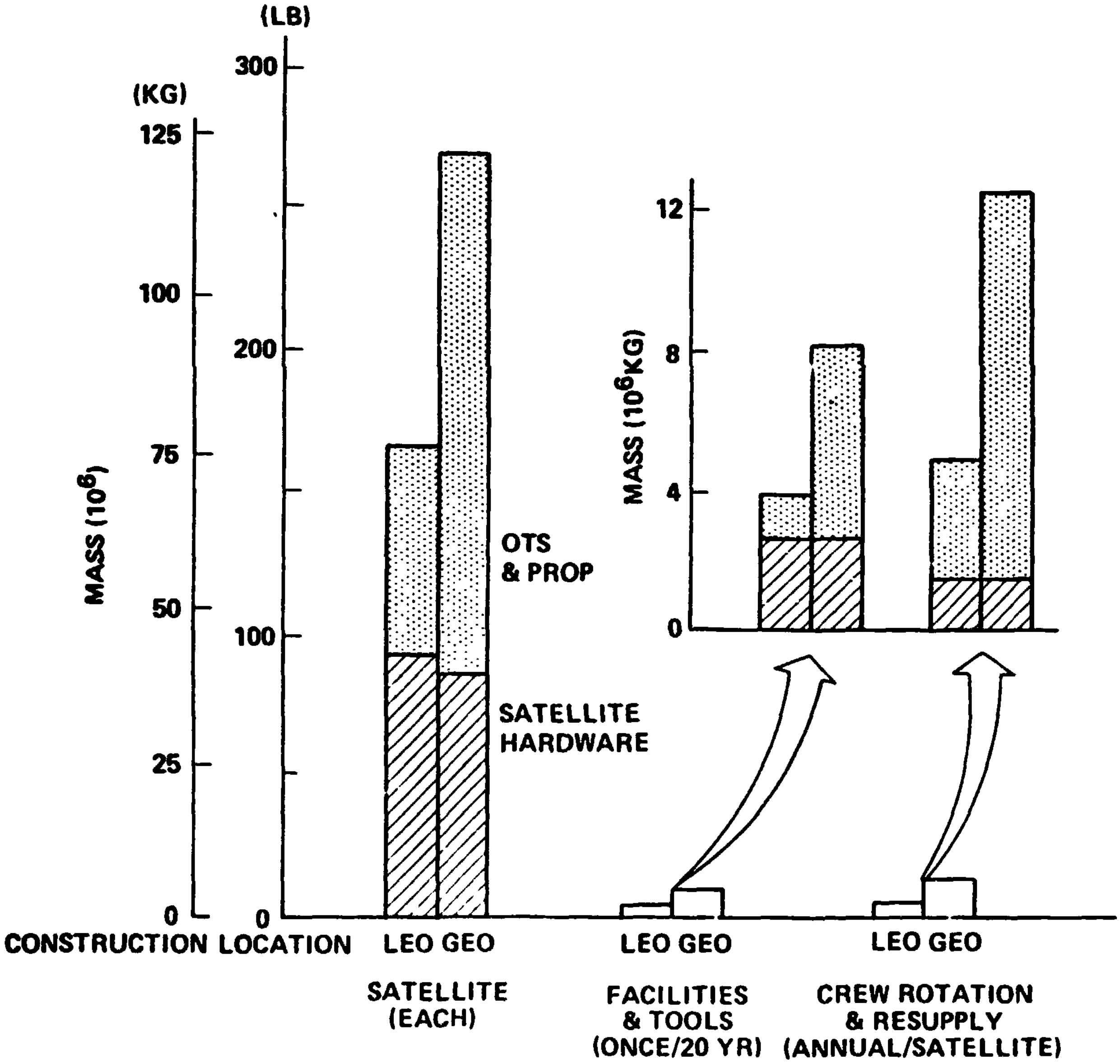


Figure 2-1 Commercial Satellite Payload Mass Summary

Rationale

The use of an equatorial launch site would offer a performance advantage of ≈25%. However, there are drawbacks, including a sea logistics line from CONUS and the construction of a complete launch processing complex from scratch. The case for equatorial launch has not been convincingly made and at any rate the earlier phases of an SPS program will undoubtedly be conducted from KSC.

Certain vehicle configurations require a downrange land landing site for the booster. In order to not preclude these configurations from consideration, alternate sites are permissible as necessary to permit their inclusion as candidate systems.

2.1.2 Destination

Requirement

The design reference destination orbit is at 477.5 km altitude and 31° inclination to the Earth's equator. Alternative design reference orbits may be selected for alternative launch sites if performance or operational advantages result. Alternative orbits shall be daily repeating at 15 orbits per day.

Rationale

The daily repeating requirement aids in simplifying and standardizing operational procedures for the high launch rates required for SPS operations. Orbit selection is a compromise involving operational convenience, atmosphere drag and radiation environment.

The low-Earth orbit should meet five primary requirements:

- o Daily repeating
- o Rendezvous–compatible, i.e., no time-consuming along-track phasing, for both of the two daily launch opportunities
- o Daily launch opportunities at least 2 hours apart
- o Altitude between 400 km and 500 km
- o Inclination not significantly greater than 28.5°

A repeating orbit of 15 orbits per day will have an altitude in the desired range. Altitude versus inclination for this orbit is given in Figure 2-2. Nodal period (time from ascending node to ascending node) was calculated by:

$$\tau = 2\pi\sqrt{\frac{a^3}{\mu}}\left\{1\text{-}3J_2\left(\frac{R^2}{a}\right)\left(\frac{7\cos^2 i\text{-}1}{8}\right)\right\}$$

with constants as follows:

μ = 398601.2 km^3/sec^2

R = 6371 km (Earth's average radius)

J_2 = 0.001082

Altitude was based on an Earth mean equatorial radius of 6378 km.

A launch window geometry was selected such that the first window occurs on a northerly pass over the launch site and the second window occurs on a southerly pass, roughly 2-1/8 revs later (Figure 2-3). The time for the combined motion of the Earth's rotation (360.9856^{o}/day) and the orbit's nodal regression (about 6.616^{o}/day) through a longitude change ΔL must equal the time required for $2 + \Delta\theta$ orbital revs. The relation between ΔL and $\Delta\theta$ are as follows:

$$\sin \Delta\theta = \cos 28.5 \sin \Delta L$$
$$\sin i = \sin 28.5 / \cos \Delta\theta$$

Simultaneous satisfaction of these requirements occurs at an inclination of 31.0 degrees; the time between windows is 3 hours and 20 minutes; the orbit altitude is 477.5 km.

The exact values computed will vary slightly with values assumed for astrodynamical constants and with inclusion of higher order gravitational harmonics. However, this orbit definition is adequate for performance and operations analyses.

2.1.3 HLLV Flight Operations

Requirement

The stage of the cargo launch vehicle that goes to orbit shall also execute on-orbit maneuvers as necessary to rendezvous and dock at an operational base in low Earth orbit, and after payload removal, shall maneuver as required to reenter and land within the designated recovery zone. The orbital stage shall be capable of a 1-day unsupported stay on orbit.

Rationale

This requirement was selected as a baseline to simplify flight operations. Alternatives include:

(1) Equipping the payload pallet system with its own OMS propulsion system so that the HLLV can be flown on a once-around trajectory. If the OMS system is expendable, its cost outweighs the HLLV performance advantage accruing from the once-around orbit. If the OMS system is to be recovered, (a) there is no evident advantage in recovering it with the HLLV as compared to the baseline requirement; (b) there are not enough crew rotation and resupply flights to recover it with the personnel vehicle.

(2) Providing a low-delta-v OTV for tug service between a low, e.g., 160 km, orbit, and the construction or staging base orbit. This option was briefly investigated by the FSTSA study and offered a slight performance advantage (Figure 2-4, concept, and 2-5, performance), at the expense of an additional system in the inventory and added operational complexity. Since the HLLV must place the payload in a stable orbit, the performance advantage is less than for the once-around insertion case.

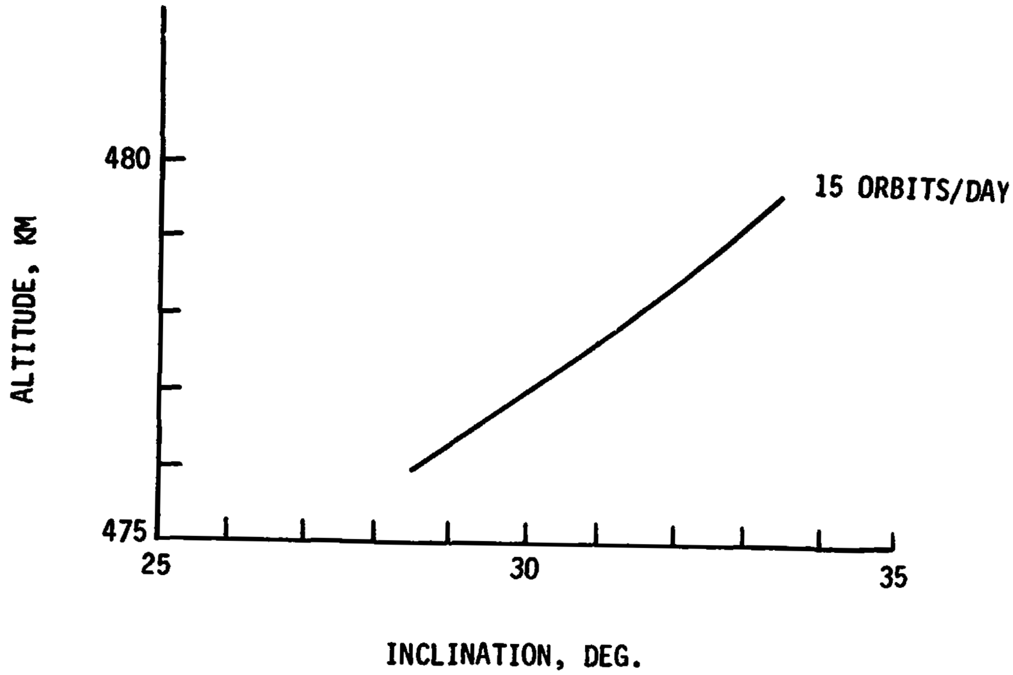


Figure 2-2 Daily Repeating Orbits

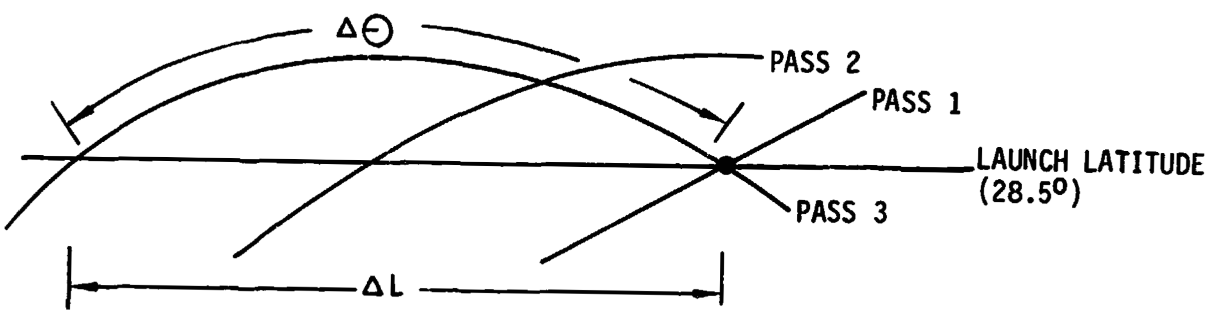


Figure 2-3 Orbit Ground Tracks

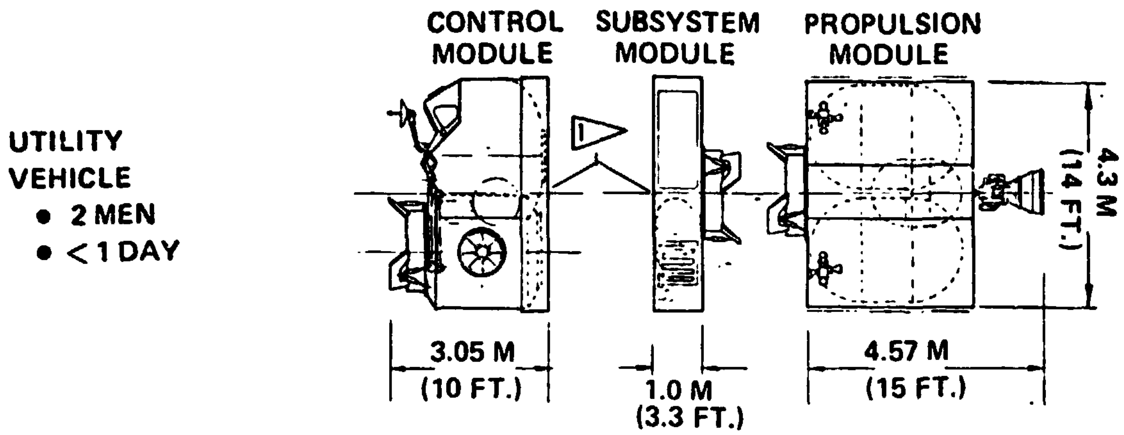


Figure 2-4 Manned OTV Utilization

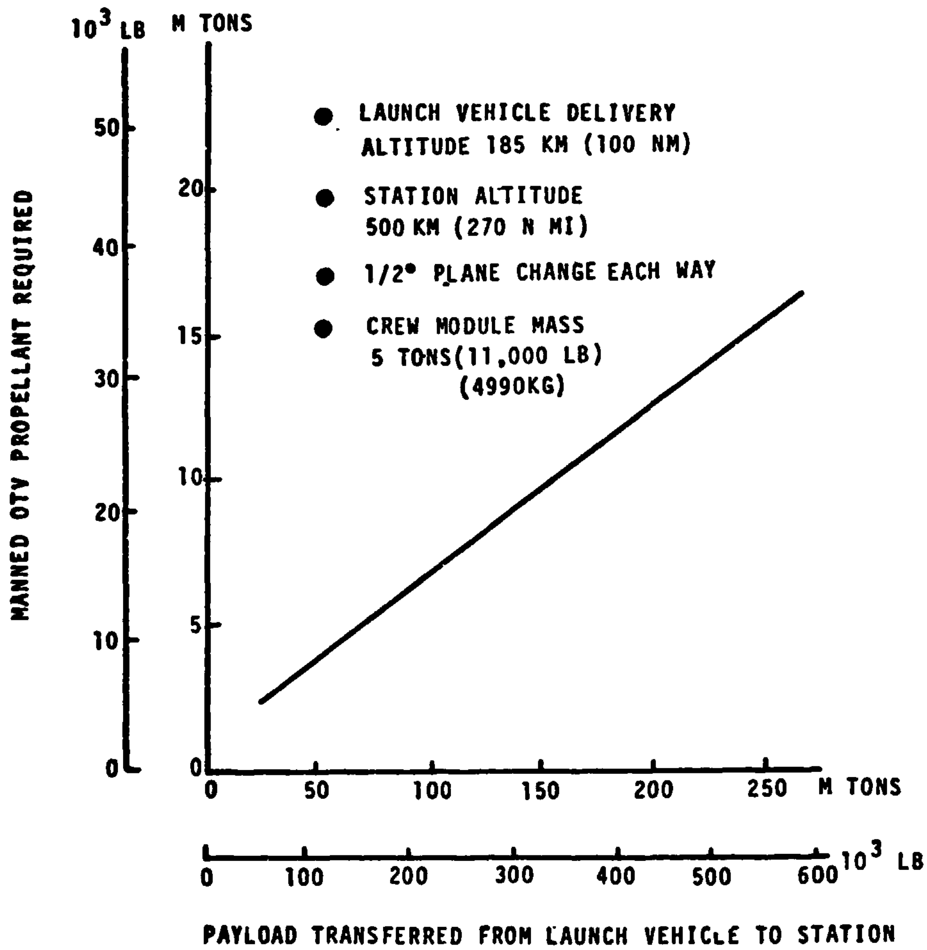


Figure 2-5 Transfer of Payloads by Low Delta V Manned OTV. Propellant Requirements

(3) Making the OMS system self-recoverable was not investigated. Self-recoverable tankers were briefly investigated by the FSTSA study (Figure 2-6).

2.1.4 Recovery Operations

Requirement

HLLV boosters shall be directly recovered following reentry from their launch trajectory. Winged boosters shall be recovered on a suitable horizontal landing runway; ballistic boosters shall be sea-recovered by powered vertical soft landing. If suitable launch and recovery siting can be provided, winged boosters may be down-range landed; otherwise they shall be capable of powered or gliding aerodynamic flight for return to the launch site. Ballistic boosters shall be down-range landed.

Upper stages, or single-stage-to-orbit vehicles, shall be recovered at a suitable recovery site after a nominal 1 day on orbit. The recovery site shall be logistically close enough to the launch site to enable the timeline requirements under para. 2.1.6 to be met. Winged stages shall be horizontal land landers and ballistic stages shall be powered vertical soft-landers designed for sea recovery. Recovery cross-range capability need only be sufficient to compensate for orbital track and reentry guidance errors. Estimated required values are 200 km for winged vehicles and 0 km for ballistic vehicles.

Reentry corridors and recovery areas shall be sited such that calculated sonic overpressures for any uncontrolled land area do not exceed 50 pascals (≈1 psf). Higher overpressures in controlled (i.e., government owned or leased) land areas are permitted.

In the event of severe weather in the launch or recovery zones, operations may be suspended to minimize crew hazards and avoid vehicle loss. Alternate recovery zones may be used when practical. The vehicle launch/recovery weather and sea state design requirements shall be selected so as to minimize expected total costs of design impact and lost operations time due to weather suspensions.

Rationale

These requirements are written around the general characteristics of winged and ballistic HLLV's as developed by the SPS Systems Study and precursor studies. Downrange booster landing provides a significant performance benefit for winged systems provided that the launch/recovery site problem can be solved. Sea landing has been selected for ballistic vehicles to eliminate terminal guidance requirements on the recovery profile. These vehicles will create significant sonic overpressures near the end of their reentry trajectory and recovery siting must deal with this problem.

2.1.5 Payload Handling

Requirement

Payload installation and removal services will be provided by appropriate support facilities. The cargo launch vehicle (HLLV) shall provide the following payload accommodations:

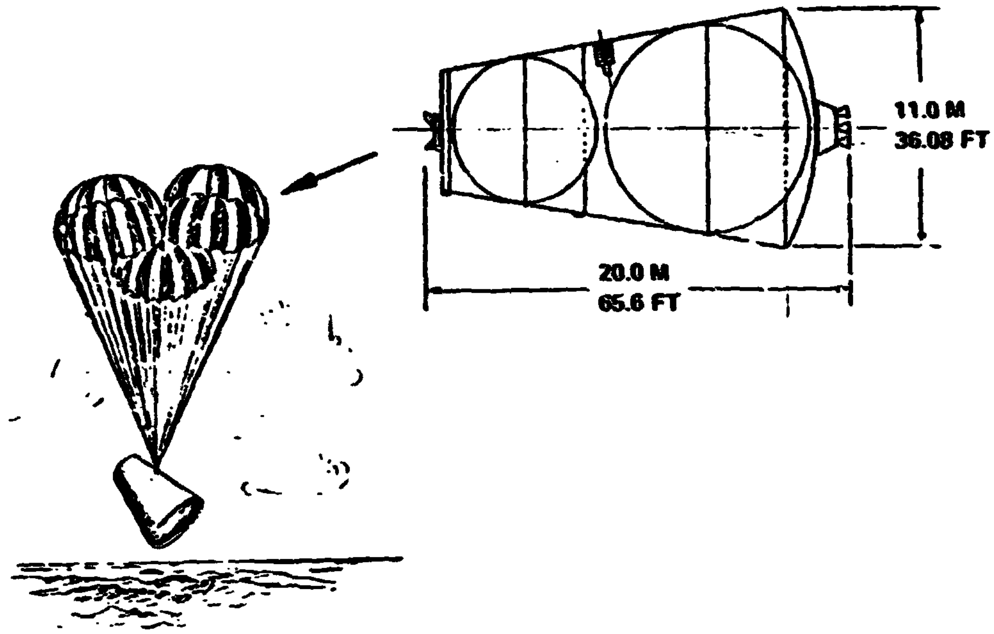


Figure 2-6 Reuseable Tanker Concept

- The HLLV shall provide a standard payload structural interface capable of accepting a standard payload pallet. Pallet installation and flight readiness verification shall require no more than six hours after the palletized payload is delivered to the launch pad. Release of the palletized payload for extraction on orbit shall be commandable by remote control.

- The HLLV shroud shall be recoverable with the vehicle and shall not be a part of the payload. The shroud shall open for top-loading of the palletized payload as an integral unit and shall provide loading clearance for payloads up to the shroud cylinder section diameter clearance limit.

- The HLLV shall provide a data interconnect suitable for carrying a payload status readout on the HLLV telemetry stream. The purpose of this is to provide the construction or operations base with advance warning of payload problems.

- The HLLV shall be capable of field alteration from SPS cargo to propellant tanker interface configuraton within 24 hours. This 24-hour period is considered additive to normal turnaround operations.

- The HLLV shall not be required to provide payload services other than those stated above. Specifically excluded are electrical or fluid services, as well as environmental control.

- Liquid propellant delivery to orbit for refueling of space-based vehicles shall be provided by a reusable tanker configuration as an HLLV payload. The tanker shall be field-interchangeable with the SPS hardware payload interface and shroud. The tanker shall include a suitable aerodynamic fairing and shall not require a shroud. Propellants for delivery to orbit shall be loaded directly into the tanker (not through the HLLV). It may be assumed that the tanker will be delivered to the orbital staging base and recovered by the HLLV, and that propellant transfer pumping and control services will be provided by the staging base. Propellant transfer ducting in the tanker shall include provisions for centrifugal phase separation.

  NOTE: Propellant may be delivered in tanks designed to be installed as part of an SPS or other spacecraft. In such cases, the propellant payload shall be designed to the standard hardware payload interface.

Rationale
These requirements are aimed at facilitating rapid and low-cost launch recycle Complex payload interfaces that might slow down turnaround operations are to be avoided. HLLV cost per flight analyses have found operations labor to be one of the primary contributors to cost per flight.

2.1.6 Turnaround Operations

Requirement
Turnaround operations shall include the following activities and nominal time allocations:

Activity	Time Allocation Ballistic/Ballistic Booster	Orbiter	Time Allocation Wing/Wing Booster	Orbiter
Entry and Landing	8 minutes	35 minutes	8 minutes	35 minutes
Acquisition by Recovery Aids	2-2/3 hours	2-2/3 hours	N/A	N/A
Return to Launch Site	16 hours	34 hours	24 hours	24 hours
Readout of Onboard BITE*	"on-board recovery ship"		2 hours	2 hours
Refurbishment and Checkout	14 hours	14 hours	14 hours	16 hours
Vehicle Integration	15 hours		15 hours	
Transfer to Launch Stand	2 hours		2 hours	
Launch Preparations	6 hours		6 hours	
Final Countdown to Liftoff	9 hours		9 hours	

*Built In Test Equipment

A vehicle requiring more than the nominal time allocation, due to abnormal conditions or service requirements, shall go off-line and be replaced by a standby (spare) vehicle. To facilitate this requirement as well as the normal turnaround sequencing, any booster shall be capable of mating with any orbiter.

Rationale
These operational characteristics resulted from HLLV operations analysis of the HLLV study (Contract NAS8-32168).

2.1.7 Abort Operations

Requirement
In the event of a mission abort for any reason, the following order of priorities shall be observed in setting abort sequences and design requirements.

(1) Avoidance of uncontrolled land impact or landing.

(2) Avoidance of uncontrolled sea impact or landing outside designated range safety or recovery areas.

(3) Avoidance of severe launch pad/facility damage.

(4) Recovery of the launch vehicle and minimization of damage.

(5) Insertion of the payload into a stable orbit from which it can be subsequently retrieved. "Stable" shall infer at least two weeks lifetime before decay.

(6) Mission completion.

Rationale
This requirement gives first priority to public and crew safety and second priority to minimization of economic loss. In general, the vehicle will be more valuable than its payload. It is expected that the cost impact of a design requirement for full payload recovery capability would exceed the expected benefits accruable on aborts.

2.2 Performance

2.2.1 Criteria

Requirement
Payload mass delivery capability shall be quoted for the design reference mission, including the following factors:

- o A flight performance reserve shall be provided, sufficient to overcome the 3-sigma (statistically-combined) case of all performance variance effects, including engine performance, propellant loading and utilization, vehicle and payload mass uncertainty, uncertainty in use of non-impulse expendables, environment factors (e.g., winds), and guidance and navigation errors. Until a suitable error analysis is available, 0.85% of the ideal ascent delta V shall be used for this reserve.

- o The delta V requirement shall include the capability to accommodate up to five minutes launch delay and shall include an additional 0.1 degree plane change capability in the on-orbit maneuver budget. This latter plane change may be combined with one of the orbit altitude change burns.

- o The design payload mass includes the pallet, any packaging provisions, and any services not stated as provided by the HLLV in Section 2.1. The payload mass does *not* include the aerodynamic shroud. If an oversized expendable shroud is fitted for abnormally bulky payloads, the difference between mass of this shroud and the standard recoverable shroud shall be charged to payload mass.

- o Propellant delivery capability shall be a derived result based on the above design payload mass and the payload-chargeable mass deltas associated with exchanging the tanker for the hardware payload interface and shroud. Propellant delivery capability shall be quoted as net after boil-off, tanker residuals and transfer losses.

Rationale
Self-explanatory.

2.2.2 Payload Mass

Requirement
The payload mass delivery capability shall be not less than 100 000 kg (100 metric tons). Values significantly greater than this may be desirable.

Rationale
SPS system studies have indicated that capabilities below this level will adversely impact SPS design. Larger payload capabilities also reduce recurring costs at high cargo rates. Vehicle studies have covered the range from 100 tons to as high as 1000 tons, with most efforts in the 200- to 400-ton range. Capability of 100 tons appears appropriate to the early phases of an SPS program, with 200 tons or more capability later as operational rates increase.

2.2.3 Payload Volume

Requirement
The minimum payload envelope dimensions shall be 8 meters diameter by 20 meters length. Ten meters diameter is highly desirable. The net payload density (mass + envelope volume) shall in no case be greater than 135 kg/M^3; 75 kg/M^3 is a design goal. Payload loading/extraction and dynamic envelope clearances shall be provided as required outside the payload envelope dimensions. The payload density requirement may be met in part by a non-cylindrical payload volume capability, provided that the minimum 8 x 20 m cylinder requirement is met.

For dynamic envelope analyses, the payload may be assumed to be an unpressurized aluminum cylinder with closed ends, and constant wall thickness, equal in size to the design payload envelope, equal in mass to the design payload mass, and supported from the aft end by the standard payload interface. Payloads requiring more dynamic envelope clearance than this dummy payload shall provide such clearance within the design payload envelope.

Rationale
Payload envelope sizes and densities stated here are estimates based on SPS packaging studies. The dynamic envelope dummy payload provides an arbitrary but specific means of establishing compliance.

2.2.4 Launch-on-time

Requirement
The HLLV shall be capable of meeting the designated departure reliability (2.2.5 below) within ±5 minutes of designated launch times. When the system is mature, up to three launches (3 vehicles) shall be possible within the ±5 minute period.

Rationale
Consistent with performance requirement; the salvo capability derives from expected operational rate requirements.

2.2.5 Reliability and Design Life

Requirement
The following nominal design reliabilities shall be met (these are expected values, i.e., 50% confidence).

(1) Probability of acceptance into normal turnaround operations after successful (non-abort) recovery–95%.

NOTE: Performance of scheduled maintenance is included within the definition of normal turnaround operations.

(2) Probability of nominal completion of turnaround–95%.

(3) Probability of successful countdown and launch following nominal completion of turnaround–99%.

(4) Probability of nominal mission completion–99%.

(5) Probability of successful recovery at end of nominal mission–99.8%.

(6) Probability of successful recovery after mission abort–75%.

The vehicle shall have a nominal design life of 300 flights in terms of fracture mechanics proof and other structural criteria. The vehicle design shall allow extension of life beyond this limit after suitable inspection, reproof, and replacement of faulty elements. The vehicle shall be designed for off-line overhaul after every 100 missions. Removal and replacement of subsystems for overhaul shall be possible to the greatest degree practicable within the normal turnaround operations.

Rationale
These are provisional requirements based on HLLV/SPS studies to date.

2.2.6 Built-in-Test and Status Monitoring

Requirement
The vehicle shall include sensors, data handling and processing, software and recording capability such that an assessment of flight readiness shall be possible within the time allocations of the nominal turnaround operations (see Section 2.1.5).

Rationale
Self-explanatory.

2.3 SUBSYSTEMS REQUIREMENTS

2.3.1 Structure

It is a design goal to minimize the use of thermal protection materials to protect the basic structure from reentry heating. Accordingly, the use of heat sink approaches and high temperature materials shall be considered for application to vehicle structure.

2.3.1.1 Propellant Tanks

Requirement

Propellant tanks shall be of welded construction fabricated from a metal alloy compatible with the propellants to be contained. Tanks shall be free-standing (not requiring internal pressure) under any propellant or payload loading condition on the pad. Tanks shall be membrane-loaded by internal pressure except for common bulkheads. Common bulkheads, if used, shall be designed to withstand any reversal pressure that can be inadvertently applied within the internal pressure ratings of the tanks. Propellant ullage space maximum design operating pressure shall be 150 kpa (22 psia) based on the following pressure budget:

Propellant saturation pressure	115 kpa	(16.7 psia)
Pressurization control minimum	+ 0 kpa	(0 psia)
Control band	+15 kpa	(2.18 psia)
Vent relief minimum	+10 kpa	(1.45 psia)
Vent relief uncertainty	+10 kpa	(1.45 psia)
	150 kpa	(22 psia)

Propellant tanks shall be designed such that a proof pressure test will validate the tanks' capability for 300 mission pressure cycles in terms of structural flaws. Propellant tanks shall be designed such that all welds are visually inspectable from at least one side and such that all welds are radiologically inspectable.

Rationale

The above requirements represent sound design practices for this reusable system.

2.3.1.2 Other Body Structures

Requirement

The body structure shall be designed and integrated with tank structures to minimize vehicle inert mass. Advanced composite materials shall be used to the maximum extent cost-effective within the thermal and other limitations of capability of such materials.

Stresses and deformations resulting from tanking cryogenic propellants, from tank pressurization, and from reentry heating shall not limit the life of body structure.

Rationale
These requirements are intended to minimize recurring cost by ensuring adequate vehicle life and minimizing maintenance costs.

2.3.1.3 Aero Surfaces and Controls

Requirement

Aero surfaces and controls shall provide aerodynamic lift and controllability as necessary to ensure safe and reliable vehicle recovery. Detailed requirements will depend on particular vehicle design characteristics. Structural design conditions to be considered for aero surfaces and controls include ascent $q\alpha$ and $q\beta$, entry, transition and pullout, and 2g subsonic maneuver. In the absence of detailed ascent simulations, a value of 3760 pascal-radians (4500 psf-deg) shall be used for ascent $q\alpha$ and $q\beta$.

Rationale
Self-explanatory.

2.3.2 Main Propulsion

2.3.2.1 Engines and Accessories

Requirements
Main engine design characteristics shall be selected to minimize system recurring costs and to minimize atmosphere pollution to the extent practicable. Present estimates of such characteristics are as follows for either winged or ballistic vehicles:

Booster Engines—Propellants shall be hydrocarbon fuel burned in liquid oxygen with sufficient liquid hydrogen used for engine cooling and pump drive. A low-mixture-ratio hydrocarbon gas generator shall not be used. Thrust chamber pressure should be in the range 14 to 30 MPa (2000 to 4400 psia) with thrust in the range 5 to 10 MN (1.1 to 2.2 million pounds). A requirement for physical interchangeability with F-1 engines may exist. This depends on programmatic aspects of the development program.

Upper Stage Engines—These engines shall be derivatives of the space shuttle main engine. Increased expansion ratio and altitude start capability will be appropriate to most vehicle designs.

Single-Stage-to-Orbit Engines—The single-stage-to-orbit engines shall provide dual-fuel capability. LO_2/hydrocarbon flow shall provide 50% of the total thrust with LO_2/LH_2 flow providing the remainder.

General For All Engines—SPS HLLV engines shall be designed for 30 missions between overhaul. Estimated burn duration per mission is 120 seconds for booster engines, 400 seconds for upper stage engines and 500 seconds for SSTO engines. SPS HLLV engines shall be designed to minimize propellant residuals, i.e. shall be capable of consuming thermally stratified propellant during the thrust cutoff transient.

The design of the engines and their feed systems shall also avoid placing a requirement on vehicle tank ullage pressure for pressure levels greater than those specified in paragraph 2.3.1.1 above.

Rationale

These engine characteristics are based on results of SPS and HLLV studies to date.

- o A strong preference for dense-fuel boosters has been found. The addition of sufficient LH_2 for engine cooling and pump drive allows operating the engine at high chamber pressure, providing higher Isp and reduced envelope. The payoff is significant. Elimination of low-mixture-ratio hydrocarbon gas generators removes a principal source of air pollution.
- o The SSME provides an adequate level of performance for upper stages. Improvement of SSME performance by larger expansion ratio is beneficial if (a) altitude start is used and (b) the vehicle envelope permits larger engine bells.
- o Dual fuel capability shows a significant advantage for vertical takeoff single-stage-to-orbit systems.
- o Engine life requirements represent projected SSME state-of-the-art.

2.3.2.2 Main Propellant Systems

Requirement

The main propellant systems shall provide onboard services for main propellant fill, feed to main engines, drain, vent, and pressurization.

The fill and drain system shall interface with launch facility services through rematable umbilical disconnects. Each stage shall provide its own umbilical locations such that inter-stage connections are not required. Ducting shall be sized to allow filling any tank with 2½ hours. Drain provisions shall allow draining any tank within 5 hours to a liquid residual quantity no greater than that normally expected at end of powered flight. The fill and drain system shall include automated interlocks to avoid inadvertent exceeding of positive or negative tank pressure design limits.

Propellant tank liquid quantity measurement shall be provided as necessary to facilitate fill, drain and in-flight propellant management.

The main engine feed system shall provide propellant feed services from tank outlet conditions to engine inlet conditions. In some cases, boost pumps may be necessary to accomplish this requirement. Acceptable boost pump drives include electrical power and main engine high pressure propellant tapoff. Separate gas generators shall not be used. The main engine feed systems shall be designed to accommodate engine gimbal motions not compensated within the engine and shall provide pressure compensation such that high gimbal torques are not produced by the motion accommodation.

The feed, fill and drain subsystems shall include passive pogo suppression devices and shall include antigeysering provisions for the tanked and holding condition.

The vent system shall:

(a) interface with the launch facility boiloff recovery system for cryogenic propellants;

(b) provide tank pressure relief backup for the pressurization system in accordance with the pressure budget under paragraph 2.3.1.1;

(c) provide sufficient vent area to accommodate a failure of the thermal insulation system if external tank insulation is used;

(d) provide tank pressure regulation by venting as required following main engine cutoff;

(e) prevent air induction into cryogenic tanks during reentry, landing and recovery operations.

Note: Normal turnaround operations will leave cryogenic propellant tanks filled with propellant vapor and non-cryogenic tanks filled with the in-flight pressurant.

The pressurization system shall:

(a) pressurize propellant tanks during engine start and run in accordance with the pressure budget of paragraph 2.3.1.1;

(b) employ as pressurants warm vapor for cryogenic propellants and a warm vapor or gas inert with respect to the propellant for non-cryogenic propellants (e.g. GN_2 or GH_2 for hydrocarbons). Scarce resources such as helium shall *not* be used.

(c) provide, if required, post-burn pressurization to maintain propellant tanks above ambient pressures during reentry, landing and recovery. (Vaporization of residuals and heat flow into the tank are expected to make this feature unnecessary.)

The main propellant system as a whole shall provide some means of preventing excessive external pressure on main propellant tanks during re-entry if a vent fails during flight.

Rationale

These design requirements evolved from the SPS and HLLV studies. Tank pressures should be kept as low as practicable to minimize inert mass. Warm pressurants minimize residuals. Boiloff recovery was shown to be cost-effective. The use of helium as a pressurant results in excessive consumption compared to expected availability.

2.3.3 Auxiliary Propulsion

Requirement

The booster auxiliary propulsion system shall provide landing propulsion as required. For ballistic vehicles, rocket propulsion shall be provided for terminal deceleration from pre-impact descent velocity (typically 150 m/sec), at approximately 4 g's, to near zero relative velocity, followed by a controlled letdown into the water at less than 3 m/sec.

For winged booster vehicles, potential needs include airbreathing propulsion for flyback and rocket propulsion for glide slope and flare control. The design objective for winged boosters, however, is to eliminate the requirements for auxiliary propulsion.

Upper stage (or single stage) auxiliary propulsion shall accomplish the following functions:

(1) Settling of main propellants following stage separation during the main engine start sequence (two-stage vehicles only). Propellant settling acceleration shall be at least 0.2 g's.

(2) On-orbit maneuvers, except those requiring attitude control or fine velocity control. (Typically, any maneuver requiring less than 10 m/sec delta may be assigned to reaction control propulsion).

(3) Landing propulsion as required. The ballistic vehicle requirement is similar to that for boosters. It is a design objective to eliminate landing propulsion requirements for winged vehicles.

Auxiliary propulsion requirements may be met, if practical, by starting or restarting some of the main propulsion engines. This option shall be traded with the option of employing dedicated engines. The upper stage propellant settling requirement may require solid propellant rockets in view of stage dynamics during separation. Solid propellants, if used, shall be a special formulation designed to minimize air pollution.

The auxiliary propulsion system (APS), with the possible exception of the post-separation propellant settling function, shall employ the same propellants as main propulsion (LO_2, LH_2 or hydrocarbon), stored in dedicated APS tanks. These tanks may be located internal or external to main propellant tanks.

Rationale
These basically represent functional requirements. Propellant quantities are great enough that toxic, corrosive, or expensive propellants should not be used. Stage separation will likely occur in the stratosphere. Post-separation ullage propulsion should avoid exhaust products (chlorides; NO_x) to which the ozone layer may be sensitive. The desire to eliminate landing propulsion for winged vehicles stems from consideration of minimizing inert mass and vehicle complexity.

2.3.4 Reaction Control System (RCS)

Requirement
The booster RCS shall orient the vehicle for reentry and shall provide control thrust as necessary to control attitude oscillations during aerodynamic entry and deceleration.

The upper stage or single-stage RCS shall, in addition to these requirements, provide thrust for attitude control on orbit, for terminal rendezvous and docking, initial separation after undock, and roll control for lift modulation if needed (aerodynamic devices for lift modulation shall be evaluated as an alternative).

The upper stage or single-stage RCS shall be configured to provide independent translateral and attitude maneuver capability. Translational capability is not required for boosters.

It is desirable from the standpoint of operational simplicity to operate the RCS on the same propellants and from the same propellant supply as the APS. The practicality of this shall be evaluated; separate propellant systems are not excluded. The upper stage or single-stage RCS shall not use propellants that produce exhaust products that will contaminate SPS systems. This exclusion precludes, for example, conventional Earth storables such as N_2O_4/hydrazine blends.

Rationale
These are basically functional requirements. Contaminating propellants are excluded because of the expected frequent arrival of HLLV's at a low Earth orbit SPS construction base.

2.3.5 Electrical Power System (EPS)

Requirement
The vehicle EPS shall store and generate and distribute electrical power as required by other subsystems. Programmed activation and cutoff of subsystems according to need shall be used to minimize power consumption, to the extent that this practice does not jeopardize attainment of vehicle reliability requirements specified in paragraph 2.2.5.

The EPS shall use batteries (booster) and batteries with fuel cells (upper stage). The EPS capacity shall be sized to allow transfer to internal power up to 10 minutes before launch and operation of recovery aids up to 1 hour (winged vehicles); 24 hours (ballistic vehicles) after landing.

Rationale

These are basically functional requirements.

2.3.6 Avionics

2.3.6.1 Guidance and Navigation

Requirement

The booster G&N system shall accept and operate on upper stage steering commands from liftoff through separation. The ballistic booster system shall provide inertial control for entry orientation and attitude control, and shall provide landing engine start and thrust control signals for landing deceleration and letdown. Water impact velocity shall be less than 3 m/sec and lateral drift velocity less than 5 m/sec, referenced to the mean water surface.

The winged booster G&N system shall provide inertial control for entry orientations and attitude control shall provide autonomous navigation to the landing recovery site to within 10 km radius, and shall provide automated landing approach and landing guidance and control with the aid of ground-based landing aids.

Upper stage (or single stage) G/N systems shall meet the above entry and landing requirements and in addition shall:

- Provide ascent navigation guidance and control through upper stage main engine cutoff. Boost phase guidance shall employ preprogrammed gravity turn with appropriate load relief.

  NOTE: Winged single-stage-to-orbit vehicles may employ lift during boost phase as appropriate to the specific vehicle design.

  Upper stage navigation and guidance shall provide adaptive path optimization to insertion conditions that maximize overall performance including on-orbit maneuvers. Insertion shall be at the perigee of a transfer orbit. The perigee shall be 100 km altitude or greater. The transfer orbit apogee shall be coincident with a phasing orbit that will compensate for launch time delays (see para. 2.2.4) in no more than 2 revs. Adaptive guidance shall include the capability to select optimal insertion conditions and phasing orbit.

- Provide autonomous navigation, guidance and control for on-orbit maneuvers through rendezvous terminal phase initiation.

- Provide navigation, guidance and control employing cooperative ranging, through the terminal rendezvous phase. Automated final rendezvous and docking may be employed employing suitable cooperative systems. The capability to accep manual command override and remote piloting (from the staging base or construction base) shall be provided.

- Provide autonomous navigation, guidance and control from separation from the base through reentry and initation of landing approach. A state vector update from the base at the time of separation may be employed.

Rationale

These are basically functional requirements. Autonomous capability is needed to minimize tracking and mission control requirements. The adaptive path optimization requirement derives from high launch rates and the need to standardize operations to 1 day on orbit. Particular attention should be given to this requirement. Launch delays will result in an along-track error on the order of 500 km/min. To make up a 5-minute delay in 2 revs will require a significant Δh between the phasing and target orbits. The optimal path must consider the ascent path, the on-orbit maneuvers and any plane change needs arising, for example, from differential nodal regression. Propellant budgeting between main and auxiliary propulsion is also involved.

2.3.6.2 Communications

Requirement

The communications subsystem shall provide tracking, telemetry and command links compatible with direct ground links, TDRSS and a construction (or staging) base-to-vehicle link. During developmental and early operational phases, full telemetry of all vehicle and payload data shall be provided. In the mature operational phase, telemetry will be confined to positional (state vector) data and out- cification conditions.

Rationale

These are functional requirements. The objective is to evolve to maximum reliance on onboard recording of data and identification of problems requiring attention by onboard diagnostic software (see para. 2.3.6.3 below).

2.3.6.3 Data Management

Requirement

The data management subsystem shall provide all onboard data acquisition, collection, distribution, formatting, processing, and disposition (including onboard recording). The data management system, when mature, shall provide (1) onboard recording of all vehicle and subsystems performance

and diagnostic data, (2) onboard recording of a summary anomaly and diagnostic data set for maintenance attention, (3) real-time telemetry of caution and warning data including onboard software-processed diagnostics for any condition that may lead to abnormal termination of the missions or hazards to ground or construction base personnel or facilities, and (4) recording of priority performance and diagnostic data on a survivable crash recorder. During all development and operational phases, the data management subsystem, interfacing with the communications subsystem, shall provide a highly reliable and secure command override link, capable of meeting all range safety and other safety requirements. This override link shall also provide for remote piloting of docking maneuvers at the construction (or staging) base.

Rationale

These requirements are intended to facilitate airline-type operations. The automated diagnostics are intended as a substitute for flight crew "squawks" which are the primary indication of maintenance needs in manned aircraft.

2.3.7 Environmental Control Systems

2.3.7.1 Cryogenic Propellants Thermal Insulation

Requirement

Thermal insulation shall be provided for cryogenic tanks and feed lines as necessary to: (1) prevent excessive boiloff; (2) prevent air or purge gas liquefaction; (3) prevent freezing of one propellant in contact with a common bulkhead separating it from a colder propellant. (These requirements are not expected to require insulation of liquid oxygen tankage.) If the basic tank structure, through use of metal honeycomb or any other insulative construction, provides sufficient thermal insulation to meet these requirements, other thermal insulation is not required. Basic tank structure should not be entered under this subsystem item.

The thermal insulation systems shall meet the vehicle requirement of 100 missions between overhauls.

The vehicles shall be purged with dry GN_2 during the prelaunch phase, as necessary, to prevent frost or ice formation internal to the vehicle. The GN_2 shall be supplied from the ground source; the vehicle requirement is to provide suitable interface connections and to provide closures of the affected dry bay areas as necessary to retain the GN_2.

Rationale

These are the usual requirements applied to cryogenic propellant insulation; the only significant new item is reusability.

2.3.7.2 Subsystems Environmental Control

Requirement

Detailed subsystems thermal control requirements have not been developed. The following general guidelines are provided:

(1) Subsystems thermal control must consider internal and external heat loads as well as cooling effects that may result from being adjacent to cryogenic systems, or in a cool air or purge gas circulation path produced by cryogenic systems.

(2) For each subsystem, a tradeoff should be conducted to determine whether: (a) the subsystem should provide its own thermal control, or (b) a vehicle system should be used. In Option (a), the vehicle may need to provide interface requirements.

(3) Thermal control requirements must address all mission phases including the turnaround operations in which the vehicle is prepared for reuse.

(4) Passive control is preferred over active systems, to the extent passive methods are practical.

(5) Sea landing vehicles shall provide environmental control such as in-flight closure of engine bell covers to prevent salt water intrusion into subsystems. Sea landing vehicles shall incorporate proven marine design practices as regards salt water compatibility.

Rationale
Self-explanatory.

2.3.8 Thermal Protection System

Definition
The thermal protection system is that subsystem which protects vehicle structure or subsystems from excessive temperature excursions due to aerodynamic or rocket plume heating. All other environmental control requirements are covered under paragraph 2.3.7.

Requirement
Thermal protections shall be provided, as necessary, to prevent temperature excursions of vehicle structure or subsystems that would jeopardize meeting vehicle performance or service life requirements. Acceptable means include heat sinks, reradiative/insulative, and active cooling. The thermal protection systems shall meet vehicle reuse timeline and service life requirements, and shall be fully reusable as defined by those requirements.

The thermal protection system shall not be a limitation on vehicle operations in terms of sensitivity to weather or other operational conditions; e.g., its performance shall not be impaired by rainfall. The TPS and vehicle design shall be such that ice shedding at liftoff will not damage the TPS or any other vehicle element. Base heat shield TPS for sea-landing vehicles shall be compatible with salt water immersion, and shall employ sound marine design practice for salt water compatibility.

Rationale

These requirements are necessary to attain the low cost and fast turnaround requirements for SPS HLLV's.

TABLE OF CONTENTS

3.0 PERSONNEL LAUNCH VEHICLES

The subject studies have generally assumed the use of a growth version of the space shuttle for personnel launch services. Relatively little study has been devoted to details of this vehicle. Only system-level requirements were developed. Personnel transportation to LEO is not a primary cost driver. If the shuttle vehicle currently under development were used, modified to meet the performance requirements of paragraph 3.2, the resulting cost would be less than 10% of the total SPS acquisition costs. Although more advanced vehicles may be desirable, they are not necessary.

3.1 OPERATIONAL REQUIREMENTS

3.1.1 Mission

Requirement
The personnel launch vehicle shall provide personnel transportation to low Earth orbit construction bases or staging bases, as applicable. The launch site and destination orbit are the same as for the cargo launch vehicle (para. 2.1.1 and 2.1.2). The personnel launch vehicle shall be capable of up to 1 week on orbit as necessary to provide for adequate tie-in between arriving and departing crews.

Rationale
Self-explanatory.

3.1.2 Launch Rate and Turnaround

Requirement
Launch rates for personnel launch vehicles as great as 250 flights per year have been identified by the SPS systems study. This rate corresponds to construction of four 10,000 megawatt SPS's per year and would occur after several years buildup of construction rate in air operational program. Shuttle turnaround times of 2 weeks appear adequate.

Rationale
These rates are based on construction crew size estimates and staytimes reported in Vol. III of this document and on the performance capabilities reflected in paragraph 3.2.

3.1.3 Operational Factors

Requirement

Desired operational features include low cost per flight and minimization of atmosphere pollution. These considerations have indicated the desirability of a fully reusable liquid booster to replace the present solid rocket boosters. Such a booster would have many of the requirements stated in Sec-

' ›n 2 for cargo launch vehicles boosters. A potential of commonality exists between a shuttle liquid booster and a cargo launch vehicle (HLLV) booster for an HLLV in the 100-ton payload class. This commonality potential should be exploited to the extent practicable.

3.2 PERFORMANCE

The (modified shuttle) personnel launch vehicle shall be capable of transporting a minimum of 50 passengers to the destination orbit (478 km, 31 degrees), and after a 7-day stay in orbit, shall be capable of returning 50 passengers to the recovery site. Passenger accommodations shall be provided by modification of the shuttle payload bay to a passenger configuration, or by installation of a passenger module in the payload bay. Passenger accommodations shall conform to applicable commercial airline Federal Air Regulations to the extent practicable and shall include additional safety and accommodation provisions as appropriate to the space mission profile. For design purposes, it may be assumed that the maximum normal passenger occupancy time in the shuttle is 12 hours each for the ascent and return mission legs. During the on-orbit stay, the passengers will be accommodated in a space-based facility.

Rationale

Preliminary studies have indicated the practicality of meeting these requirements with the shuttle. Seat widths and pitch and aisle width sufficient to accommodate more than 50 space-suited passengers are possible. Shirt-sleeve accommodations for a greater number could be provided. At present it is not clear whether suited or shirt sleeve accommodations should be employed.

TABLE OF CONTENTS

4.0 HIGH THRUST ORBIT TRANSFER VEHICLES

4.1 OPERATIONAL REQUIREMENTS

High thrust orbit transfer vehicles shall provide orbit-to-orbit transportation for cargo and personnel between low earth orbit and geosynchronous orbit. Design objectives are low cost, fast turnaround, flexible operation capability and efficiency. The vehicle shall be designed to be staged as necessary to maximize efficiency and minimize recurring costs.

4.1.1 Mission

Requirement
The design reference mission shall be round trip transfer from low earth orbit at 478 kilometers altitude, 31° inclination to geosynchronous orbit at any desired target longitude. Alternate design missions may be specified if an alternate mission orbit is selected for the Earth launch systems. The vehicle design shall permit any alternative mission profile that is possible based on the propellant loadings, consumables loading, and mission duration that result from the design mission. The uppermost stage of the vehicle shall be operable independently without booster stages for those missions within its capability in terms of propellant loading and mission duration.

Rationale
This mission requirement is based on the staging base or construction base orbit specified for Earth launch system. The Earth launch vehicles and orbit transfer vehicles, operating together, provide a complete transportation system for Earth to geosynchronous orbit operations.

4.1.2 Operational Characteristics

Requirement

The orbit transfer vehicle shall be designed to use liquid oxygen, liquid hydrogen propellants and it is a design goal to avoid the use of other fluids requiring resupply during the operational life of the system. The vehicle shall be designed for in-space servicing between missions with a maximum servicing timeline of 2 days from docking at the low orbit base until readiness for the next mission. The vehicle shall provide automated onboard status monitoring and built-in test with diagnostic software to minimize the need for launch readiness testing at the low orbit base.

The vehicle shall provide propellant transfer interconnects such that:

(a) Each stage can be refueled independently or both can be refueled with the stages docked together in normal flight configuration. Stages or the assembled vehicle shall be forward-end docked to the facility for propellant transfer.

(b) The vehicle transfer ducting is compatible with centrifugal phase separation (swirling the propellants within the tanks) during transfer.

(c) Transfer boiloff can be returned to the facility.

The vehicle shall provide a command and display digital interface to crew modules such that it can be piloted from the crew module, if desired. The vehicle shall also be capable of autonomous navigation, guidance, and control on the nominal mission profile (see Section 4.2 below), except for terminal rendezvous and docking.

Rationale
Space-basing was selected as the preferred operational mode in the transportation add-on to the SPS system definition study. Centrifugal phase separation was selected as the preferred transfer mode.

4.1.3 Payload Accommodations

Requirement

The orbit transfer vehicle shall provide a standard docking interface for docking to all payloads. Provision of mating hardware for matching to this interface will be the responsibility of the payload. The docking interface will provide only structural attachment and a data interconnect. No other payload services will be provided by the OTV. Personnel transportation shall be accommodated by a semi-autonomous crew module that provides its own services with only structural and data interfaces with the orbit transfer vehicle.

Cargo payloads shall be configured to fit the same structural interface as the crew module and payload hardware will be palletized to the extent necessary to achieve this requirement. Release of the payload from the OTV shall be commandable by remote control. Detailed structural requirements and configuration of the interface are TBD.

4.1.4 Abort and Safety

Requirement
The vehicle shall be suitable for manned operation in that no single failure shall cause mission abort. No identifiable failure or combination of failures shall cause loss of crew. For manned operations the vehicle instantaneous state vector at all times shall represent a stable earth orbit from which a rescue could be accomplished.

Abort modes shall be:

(1) Immediate return to the most easily reachable space base.

(2) If that is not possible, perform any possible maneuver that will improve rescue capability and await rescue by another OTV.

Rationale
These requirements exploit the characteristic of orbital flight that a cessation of propulsion will not lead directly to a crash. Because of this, the use of rescue modes is the most straightforward means of handling aborts.

4.2 PERFORMANCE

4.2.1 Payload Capability

Requirement
The OTV shall be sized to deliver one cargo launch vehicle payload from LEO to GEO on the design reference mission, with no return payload. Personnel transport capability will be a derived capability based on round trip transportation of passengers.

Flight performance reserves for each stage of the OTV shall be 2% of the translational delta budget assigned to that stage. Reserves shall be applied by including the reserve as a pseudo-maneuver at the end of the mission profile. The pseudo-maneuver shall include the payload carried on the last real maneuver. These reserves are intended to allow for navigation and guidance errors.

Finite burn losses, nominal course corrections, and rendezvous and docking requirements shall be included in maneuver delta v budgets. Finite burn loss calculations shall include the effects of reduction in plane charge thrust vector effectiveness due to the path length traversed during the finite burn, as applicable.

The design payload mass includes pallets, packaging provisions, and any services not stated as provided by the OTV in Section 4.1.3 above. The HLLV pallet (see 4.2.2 below) may be partitioned such that structural members needed to carry launch loads (4-5g) may be removed before installation on the OTV, provided that the partitioning does not involve repacking the payload.

Rationale
Self-explanatory.

4.2.2 Payload Mass Capability

Requirement

The OTV shall be sized to deliver one cargo launch vehicle payload from LEO to GEO on the design reference mission, with no return payload. Personnel transport capability will be a derived capability based on round trip transportation of passengers. The OTV shall be capable of transferring empty to GEO and returning a payload with return payload capability limited only by vehicle propellant loading. This capability will be a derived capability based on the vehicle sizing criterion used.

Rationale

Sizing the OTV to handle one HLLV payload avoids payload repacking or reconfiguration at the LEO base. No evident advantages were seen in making the OTV smaller.

4.2.3 Payload Volume

Requirement

The OTV shall place no restrictions on payload volume. Payloads may be restricted to have no extensions aft of the docking interface plane that might interfere with fields of view of OTV sensors. Payloads may also be restricted in terms of center of gravity offset and stiffness, in order to ensure controllability of the OTV. These restrictions are TBD.

Rationale

The non-restriction of payload volume is in order to allow payloads to be partially deployed, erected, or constructed at the staging base, if desired.

4.2.4 Mission Timeline and Delta V Budget

Requirement

The nominal design reference delta v budget and mission element time allocations are stated in Table 4-1, for a two-stage OTV with equal volumes of main propellant tanks for each stage. Mission durations as long as 30 days shall be possible with the added propellant boiloff and additional consumables charged against payload capability. The delta v split between items 3 and 5 is a function of vehicle assumptions; values used to derive the split shown are as follows:

Table 4-1 – Mission Profile for LO_2/LH_2 OTV LEO-GEO Freight Operations

MISSION EVENT NO. & NAME		REQUIRED TIME (HR)	DELTA V M/SEC	REQUIRED PROPULSION TRANSLATIONAL OR MANEUVERING	REMARK
			MISSION		
1.	STANDOFF	0	3	M	PROVIDES SAFE SEPARATION DISTANCE BETWEEN FACILITY & VEHICLE
2.	PHASE	12	3	M	ΔV IS ATTITUDE CONTROL
3.	BOOST	.5	1715	T	OTV BOOST STAGE SEPARATES AFTER THIS ΔV
4.	COAST	4.2	3	M	ELLIPTIC REV
5.	INJECT	.1	750	T	INCLUDES 60 M/SEC ACCUMULATED FINITE-BURN LOSS
6.	COAST	5.4	3	M	TRANSFER TO GEO
7.	PHASE INJ	.1	1780	T	REPRESENTATIVE FOR 15° PHASING
8.	PHASE	23	3	M	
9.	TPI (TERMINAL PHASE INITIATION)	.1	55	T	INCLUDES 15 M/SEC OVER IDEAL TO ALLOW FOR CORRECTIONS
10.	RENDEZVOUS	2	10	M	TPI ASSUMED TO OCCUR WITHIN 50 KM OF TARGET
11.	DOCK	1	10	M	
12.	PAYLOAD REMOVAL	8	0	–	ASSUMED DOCKED
13.	STANDOFF	.1	3	M	
14.	DEORBIT	.1	1820	T	
15.	COAST	5.4	10	M	TRANSFER TO LEO
16.	PHASE INJECT	.1	2356	T	.
17.	PHASE	12	3	M	ORBIT PERIGEE AT STAGING BASE ALTITUDE
18.	TPI	.1	50	T	
19.	RENDEZVOUS	2	20	M	
20.	DOCK	1	10	M	
21.	RESERVE	–	130	(T)	2% OF STAGEΔV BUDGET
			BOOSTER RECOVERY		
1.	COAST	4.2	30	T	ΔV TO CORRECT DIFFERENTIAL NODAL REGRESSION BETWEEN COAST ORBIT AND STAGING BASE
2.	PHASE INJECT	.1	1645	T	ELLIPTIC ORBIT-PERIGEE AT STAGING BASE ALT.
3.	PHASE	12	3	M	ALTITUDE CONTROL
4.	TPI	.1	50	T	
5.	RENDEZVOUS	2	20	M	
6.	DOCK	1	10	M	
7.	RESERVE	–	85	(T)	2% OF STAGE ΔV BUDGET

Main engine Isp 470 sec	
Auxiliary Propulsion Isp 220 sec	
Start loss, including effective loss due to reduced Isp in THI mode	Stg 1 - 100 kg per start
	Stg 2 - 50 kg per start
Stop loss	Stg 1 - 20 kg
	Stg 2 - 10 kg
Boiloff Rate	6 kg/hr each stage

Burnout Mass Scaling Equations:

Stg 1 3430 kg + 0.05567 WP_1 + 0.1725 WP_2

Stg 2 3800 kg + 0.05317 WP_1 + 0.1725 WP_2

where WP_1 and WP_2 are main and auxiliary propellant capacities respectively.

This split shall be adjusted as necessary to best adapt to the vehicle design and the booster recovery profile modified accordingly. For a single-stage vehicle, items 3 and 5 may be combined into a single burn (item 4 eliminated). Booster recovery is not applicable to a single-stage system.

The nominal delta v budget shall be modified as appropriate to vehicle design characteristics and improved definition of requirements and non-ideal losses. Modifications shall retain the phasing operations flexibility represented by the nominal design reference mission.

Rationale

Orbit transfer timelines include necessary phasing operations. The low-Earth orbit nodal period is 5645 sec (1.568 hours) so that the longitude shift per rev is 24 degrees. Thus GEO longitude destinations for transfer opportunities, which occur at every nodal crossing, are spaced at 24 degree intervals. Waiting in LEO for the best transfer opportunity will permit arrival at GEO within 24° of the desired longitude. The wait period will not exceed 24 hours; 12 hours is a representative value. Upon arrival at GEO, a phasing orbit is used with period up to 1.6 hours less than the GEO orbit period of 23.934 hours. The phasing orbit period should always be less than the GEO period; the GEO circularization then occurs in two burns that ideally sum to the delta V required for a single burn injection. A wait period at GEO is also required to permit the return transfer to always be coplanar with the staging base orbit. Further phasing will, in general, be required after return to the staging base orbit since the GEO mission will ordinarily not be synchronized with the staging base orbit period.

The elliptic rev parking orbit period is dependent on boost delta V. The value shown in Table 4-1 was selected to equalize propellant loading between the two OTV stages.

Representative results are shown in Figure 4-1, indicating a total boost delta V, including finite burn losses, of 1715 m/sec. The relationship between booster delta V and elliptic orbit period is shown in Table 4-2 and Figure 4-2.

Orbit transfer vehicle performance requirements include equivalent impulsive maneuver delta v's with additions for finite burn losses, phasing maneuvers, course corrections, and attitude control requirements. The impulsive delta v's assumed 2.5° of plane change for the LEO burns and 28.5° of plane change for the GEO burns. Circular orbit velocities at LEO (477.5 km) and GEO were computed as 7625.2 m/sec and 3074.7 m/sec respectively. Perigee and apogee velocities in the transfer ellipse were computed as 10001.2 m/sec and 1626.1 m/sec respectively. Transfer delta v's were computed by:

$$\Delta V = \sqrt{V_1{}^2 - 2V_1V_2 \cos \Delta p + V_2{}^2}$$

and evaluated as 2406 m/sec and 1820 m/sec for perigee and apogee burns, respectively.

4.2.5 Launch-on-Time

Requirement
The vehicle shall initiate all maneuvers within ±15 seconds of the computed optimal initiation time.

Rationale
This is an estimated maximum desirable time uncertainty to minimize performance penalties for corrections. No effect on vehicle design has been identified attributable to this requirement.

4.2.6 Reliability and Design Life

Requirement
The following nominal design reliabilities shall be met (these are expected values, i.e., 50% confidence).

1. Probability of acceptance into normal turnaround operations after successful (non-abort) recovery-95%.
   NOTE: Performance of scheduled maintenance is included within the definition of normal turnaround operations.

2. Probability of nominal completion of turnaround-95%.

3. Probability of successful mission initiation following nominal completion of turnaround-99%.

4. Probability of nominal mission completion-99%.

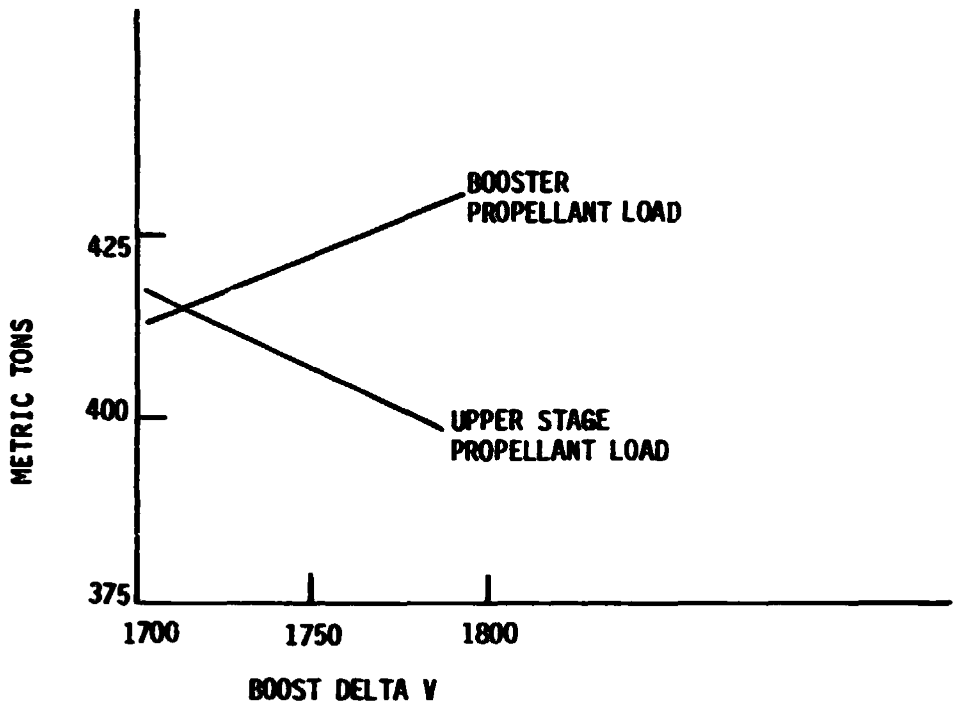


Figure 4-1 Selection of Boost Delta V

Table 4-2 Elliptic Coast Orbit Parameters

IMPULSIVE ΔV	V_p	r_a	a	τ
0	7625.2	6855.5	6855.5	1.569
1	8625.2	12174	9514.7	2.566
1.5	9125.2	172[illegible]	12072	3.667
1.75	9375	21222	14039	4.60
2	9625	26863	16859	6.05
2.1	9725	29869	18362	6.878
2.2	9825	33504	20180	7.925
2.3	9925	37988	22422	9.282
2.4	10025	43656	25256	11.095
2.5	10125	51049	28953	13.619

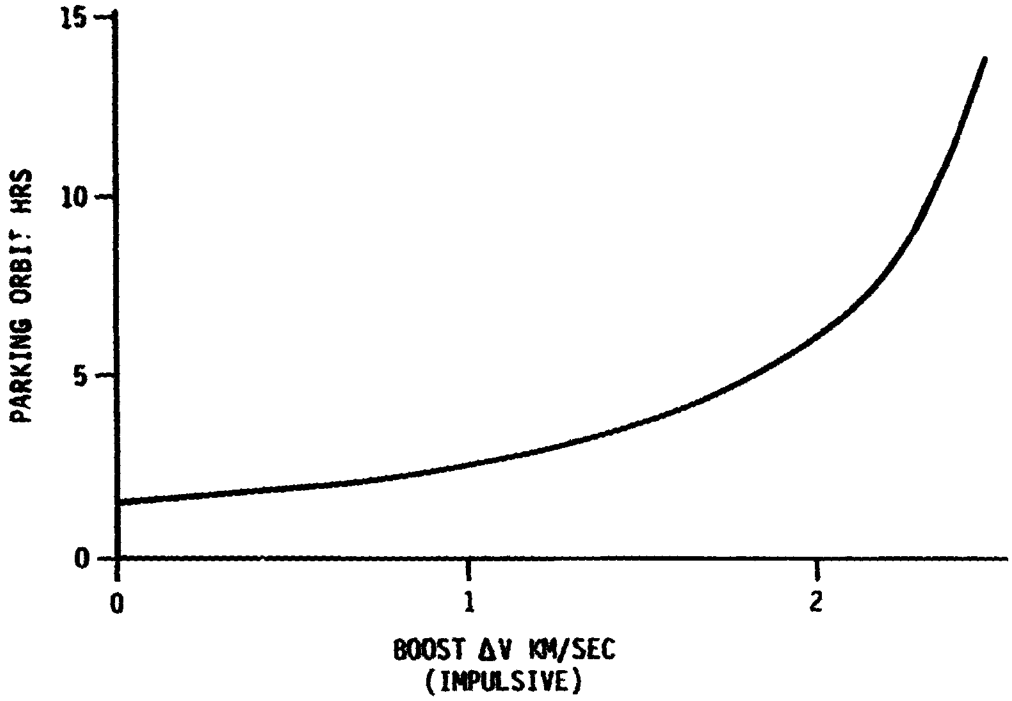


Figure 4-2 Parking Orbit Period

5. Probability of loss of crew - not calculable. These shall be no identifiable failure modes that cause loss of crew (ref. 4.1.4).

The orbit transfer vehicle shall be completely reusable and shall have a nominal design life of 50 flights in terms of fracture mechanics proof and other structural criteria. The vehicle design shall allow extension of life beyond this limit after suitable inspection, reproof, and replacement of faulty elements. For purposes of design life analysis, missions shall be assumed to occur on one-month centers. Removal and replacement of subsystems for overhaul shall be possible to the greatest degree practicable within the normal turnaround operations.

Rationale
These are provisional requirements based on SPS transportation studies to date.

4.2.7 Built-in-Test and Status Monitoring

Requirement
The vehicle shall include sensors, data handling and processing, software and recording capability such that an assessment of flight readiness shall be possible within the time allocations of the nominal turnaround operations.

Rationale
Onboard automated system/subsystem performance monitoring with diagnostic software will facilitate fast and efficient turnaround operations.

4.3 SUBSYSTEMS REQUIREMENTS

4.3.1 Structures

Requirement
Structural design loads shall be based on the assumption of launch from earth empty with a maximum launch vehicle acceleration of 5 g's. Structural design loads for OTV flight operations will depend on installed thrust. A startburn acceleration of 1.5 m/sec^2 is a typical optimal value.

Rationale
Launch empty with space basing results in a significant decrease in inert mass, due to reduced loads.

4.3.1.1 Main Propellant Tankage

Requirement
Propellant tanks shall be of welded construction, fabricated from a metal alloy compatible with the propellants to be contained. Tanks shall be free standing (not requiring internal pressure) under any

loading conditions. Tanks shall be membrane-loaded by internal pressure except for common bulkheads. Common bulkheads, if used, shall be designed to withstand any reversal pressure that can be inadvertently applied within the pressure ratings of the tanks. The ullage pressure budget is the same as given in paragraph 2.3.1.1.

Tankage design shall be based on a design life of 50 missions with 10 pressure cycles per mission with the pressure varying from 100 kilopascals to 150 kilopascals for each cycle.

Propellant tanks shall be designed such that all welds are visually inspectable from at least one side and such that all welds are radiologically inspectable.

Rationale

Good design practice for this reusable system. The ten pressure cycles per mission result from multiple engine starts per mission.

4.3.1.2 Other Body Structures

Requirement

The body structure shall be designed and integrated with tank structures to minimize vehicle inert mass. Advanced composite materials shall be used to the maximum extent cost-effective within the thermal and other limitations of capability of such materials.

Stresses and deformations resulting from tanking cryogenic propellants, from tank pressurization, and from re-entry heating shall not limit the life of body structure.

Rationale

These requirements are intended to minimize recurring cost by ensuring adequate vehicle life and minimizing maintenance costs.

4.3.2 Main Propulsion

4.3.2.1 Main Engines

Requirement

The main propulsion system shall utilize liquid oxygen, liquid hydrogen propellants at a nominal mixture ratio of 5.5. The main propulsion engine shall provide a start burn acceleration for each stage of 1.5 m/sec^2 (representative optimal value. The acceleration may be optimized to maximize stage performance and may be adjusted to practical engine sizes and clustering configurations).

The main propulsion engines shall be designed to provide as high an ISP as is practicable. A target value is 470 seconds.

The main propulsion engines shall provide for self-ullaging and tank head start from saturated or mixed phased propellants initially supplied at 125 kilopascals tank pressure. Throttling is not required. Separately driven boost pumps may be employed if mass or performance advantages thereby are accrued, but shall be driven by main engine tap-off during mainstage operations.

Main engines shall be gimballed through a square pattern gimbal angle of 6 degrees to provide for stage attitude control during main engine burns.

It is a design goal to attain a main engine 50 missions life without overhaul. At a representative vehicle installed thrust, this translates to 300 starts and 30 hours of engine life. An option to meet the vehicle design life is to design the engine/vehicle interface so that engines can be changed out as a part of the service cycle, with engines returned to Earth (by the Shuttle) for overhaul.

Rationale
OTV optimization studies have found that a mixture ratio of 5.5 and start burn acceleration of 1.5 m/sec^2 provides optimal performance, considering variations in inert mass, Isp, and finite-burn losses. Low feed pressure is essential to minimize tankage mass. The start requirements are intended to maximize performance and avoid need for a separate pressurization system. The engine life requirement is recognized as a difficult goal; an optional overhaul approach is accordingly provided.

4.3.2.2 **Main Propellant Systems**

Requirement
The main propellant systems shall provide onboard services for main propellant fill, feed to main engines, drain, vent and pressurization.

The fill and drain system shall interface with supprt facility services through rematable umbilical disconnects. Each stage shall provide umbilical locations such that each stage can be independently tanked or the stages can be tanked through suitable inter-stage connections when docked together. Ducting shall be sized to allow filling any tank within 2 1/2 hours. Drain provisions shall allow draining any tank within 5 hours. The fill and drain system shall include automated interlocks to avoid inadvertent exceeding of tank pressure design limits. Transfer pumping will be provided by the support facility (staging base).

Propellant tank liquid quantity measurement shall be provided as necessary to facilitate fill, drain and in-flight propellant management.

The main engine feed system shall provide propellant feed services from tank outlet conditions to engine inlet conditions. In some cases, boost pumps may be necessary to accomplish this requirement. Acceptable boost pump drives include electrical power and main engine high pressure propellant tapoff. Separate gas generators shall not be used. The main engine feed systems shall be

designed to accommodate engine gimbal motions not compensated within the engine and shall provide pressure compensation such that high gimbal torques are not produced by the motion accommodation.

The feed, fill and drain subsystems shall include passive pogo suppression devices.

The vent system shall:

(a) interface with the facility boiloff recovery system for cryogenic propellants;

(b) provide tank pressure relief backup for the pressurization system;

(c) provide sufficient vent area to accommodate a failure of the thermal insulation system if external tank insulation is used;

(d) provide tank pressure regulation and propellant conditioning by venting as required following main engine cutoff;

Note: Normal turnaround operations will leave cryogenic propellant tanks filled with propellant vapor and any non-cryogenic tanks filled with the in-flight pressurant.

The pressurization system shall:

(a) pressurize propellant tanks during engine start and run.

(b) employ as pressurants warm vapor for cryogenic propellants and a warm vapor or gas inert with respect to the propellant for non-cryogenic propellants (e.g., GN_2 or GH_2 for hydrocarbons). Scarce resources such as helium shall not be used.

Rationale
These design requirements evolved from FSTSA and SPS studies. Tank pressures should be kept as low as practicable to minimize inert mass. Warm pressurants minimize residuals. Boiloff recovery was shown to be cost-effective. The use of helium as a pressurant may result in excessive comsumption compared to expected availability.

4.3.3 Auxiliary Propulsion

Requirement
The auxiliary propulsion system shall provide for all low-delta v maneuvers for which the main propulsion system is not suitable, and shall provide all required altitude control maneuver capability.

It is a design objective that the auxiliary propulsion system employ the same propellant as the main propulsion system in order to simplify on-orbit servicing. The auxiliary propulsion system shall avoid the use of propellants that would result in contamination of payloads by thruster exhaust. Auxiliary propellant may be fed from tanks separate from the main propulsion system as appropriate to optimization of the auxiliary propulsion system. The auxiliary propulsion system shall be capable of utilizing its propellant in any sequence relative to the main propulsion system. (Operation of the main propulsion system shall not be relied upon to recharge auxiliary propulsion tanks).

The auxiliary propulsion shall be capable of operating in any sequence of pulse and continuous burn modes, limited only by propellant capacity. It is a design objective that the auxiliary propulsion system not employ intermittently operating mechanical pumping systems to provide propellant pressure.

Thrust level for the auxiliary propulsion shall be sufficient to provide an axial acceleration, at the point in a nominal mission profile where docking is required, of .05 meters per second squared. The auxiliary propulsion system will be configured such that fully independent translational and rotational control of the vehicle is possible without gimballing thrusters.

Rationale

The performance benefit accruing from use of high-Isp propellant in the auxiliary propulsion system is minimal. The principal driver is on-orbit servicing simplicity. OTV's as defined by the FSTSA study required four or more fluids (O_2, H_2, He, N_2H_4). It is highly desirable to reduce this number to two. Some helium pre-pressurization may be needed for main propellants to minimize mass transfer across the liquid/gas interface, but should be avoided if practicable. Other auxiliary propulsion requirements are derived from the mission requirements. The acceleration figure is a preliminary estimate of capability required for rendezvous and docking.

4.3.4 Electrical Power System

Requirement

The electrical power system shall provide the electrical power needs of the other vehicle subsystems. Power shall be provided rough regulated with fine regulation provided at use points. The power generation system shall employ hydrogen-oxygen fuel cells fueled either by separate tanks or by the propellant tanks that feed the auxiliary propulsion system. Approximate power requirements are 1 kilowatt average, 5 kilowatts peak.

Programmed activation and cutoff of subsystems according to use shall be used to minimize power consumption, to the extent that this practice does not jeopardize attainment of vehicle reliability requirements specified in Paragraph 4.2.6.

Emergency batteries shall be provided with sufficient capacity to maintain the vehicle in a powered-down but controllable state for 7 days in order to provide time for a rescue from an abort-situation. This requirement shall apply to cargo or crew missions. Crew module emergency power will be provided by the crew module electrical power subsystem. Power transfer between the OTV and crew modules shall be possible in emergencies, but each system will usually provide its own power.

Rationale
These are basically functional requirements.

4.3.5 Avionics

4.3.5.1 Guidance, Navigation and Control

Requirement
The GN&C system shall provide autonomous control of the OTV through all elements of the nominal mission profile excepting terminal rendezvous and docking. The GN&C systems shall provide for remote piloting override for these latter functions and may include automated terminal rendezvous and docking with suitable cooperative target systems.

The GN&C system shall provide automated mission planning and targeting to accommodate the variations in the nominal mission profile that result from variations in low Earth orbit altitude, inclination and line of node, and variations in the target longitude in geosynchronous orbit.

The GN&C system shall use an appropriate combination of stellar-inertial and cooperative target references.

Rationale
These are basically functional requirements. Autonomous capability is needed to minimize tracking and mission control requirements. Automated mission planning and targeting is highly desirable to simplify operations.

4.3.5.2 Communications Subsystem

Requirement
The communications subsystem shall provide for tracking, command, and control through external sources by suitable RF links. Communications capability shall exist for communicating with ground stations either direct or through TDRSS, with space shuttles, and with orbital operations bases in low Earth orbit and geosynchronous orbit. The use of steerable antennas and selective vehicle attitudes to enhance communications shall be avoided to the extent practicable.

During developmental and early operational phases, full telemetry of all vehicle and payload data shall be provided. In the mature operational phase, telemetry will be confined to positional (state vector) data and out-of-specification conditions.

It is not a requirement on the OTV communications subsystem to provide for crew voice links or other communications, when the crew module is present. That service shall be provided by the crew module itself.

Rationale
These are functional requirements. The objective is to evolve to maximum reliance on onboard data recording and identification of problems requiring attention by onboard diagnostic software (see paragraph 4.3.5.3 below).

4.3.5.3 Data Management Subsystem

Requirement
The data management subsystem shall provide all onboard data acquisition, collection, distribution, formatting, processing, and disposition (including onboard recording). The data management system, when mature, shall provide (1) onboard recording of all vehicle and subsystems performance and diagnostic data, (2) onboard recording of a summary anomaly and diagnostic data set for maintenance attention, and (3) realtime telemetry of caution and warning data including onboard software-processed diagnostics for any condition that may lead to abnormal termination of the missions of hazards to flight crew or construction base personnel or facilities. During all development and operational phases, the data management subsystem, interfacing with the communications subsystem, shall provide a highly reliable and secure command override link, capable of meeting all range safety and other safety requirements. This override link shall also provide for remote piloting of docking maneuvers at the construction (or staging) base.

The data management subsystem shall also provide for automated monitoring of vehicle condition and automated built-in test prior to initiation of major mission events. The data management subsystem shall be the interfacing subsystem for control and display data, interfacing with a crew module when present as a payload of the OTV.

It is a design objective to use advanced processor and memory technology with high level languages to the degree possible.

Rationale
These requirements are intended to facilitate airline-type operations. The automated diagnostics are intended as a substitute for flight crew "squawks" which are the primary indicator of maintenance needs in manned aircraft.

4.3.6 Thermal Control Subsystem

Requirement

Passive thermal control shall be utilized throughout the OTV system. Propellant management thermal control shall be accomplished by a combination of multi-layer insulation, minimum heat leak structures design, and propellant venting as appropriate to control tank pressure buildup. A non-degrading base heat shield shall be provided to control the thermal environment resulting from the main engine firing. Thermal control of the avionics subsystem shall be provided by the use of cold plates, with semi-passive louvered radiators as necessary. The use of heaters shall be minimized but is permissible in special cases where the thermal environment for subsystem elements is otherwise not controllable. A combination of appropriate levels of insulation and heaters shall be used for thermal expulsion of propellants for fuel cells and auxiliary propulsion if required by the subsystem design.

Rationale

These are basically functional requirements. Passive systems will reduce cost and operational problems.

TABLE OF CONTENTS

5.0 ELECTRIC ORBIT TRANSFER SYSTEM REQUIREMENTS

The electric orbit transfer system (OTS) is a set of equipment to be installed on a solar power satellite module in order to convert the module to a powered spacecraft that can propel itself from low Earth orbit to geosynchronous orbit by electric propulsion, using electric power produced by the module. Since the electric orbit transfer system is not in itself a distinct vehicle, its requirements are less well-defined than those for the vehicles addressed by section 2, 3, and 4.

5.1 OPERATIONAL REQUIREMENTS

5.1.1 Mission

Requirement

The design reference mission shall be a one-way transfer from a low Earth orbit at 478/cm altitude, 31° inclination, to geosynchronous orbit at 0° inclination and any designated longitude. It may be desirable to provide capability to return some of the orbit transfer system hardware to LEO for reuse; if provided, this capability shall employ a high-thrust chemical system. Minimum cost is indicated if the high-thrust return system is delivered to GEO as a part of the OTS to take advantage of the high specific impulse of the electric propulsion system.

Rationale

This mission requirement is based on the construction base orbit specified for Earth launch systems. Studies of the re-use of OTS hardware have not yet reached a firm conclusion and further investigation is warranted.

5.1.2 Operational Characteristics

Requirement

The orbit transfer system shall be designed to employ propellants available in adequate quantities, e.g., not mercury. (Argon has been assumed in FSTSA and SPS studies). The orbit transfer system shall provide hydrogen/oxygen chemical propulsion capability as required to maintain attitude control of the satellite. This capability requirement is presently estimated as requiring chemical thrust capability equal to electric thrust, about 1/10 the total propellant load as LO_2/LH_2, and capability to operate in pulse mode as well as steady state. The chemical thrusters shall be installed such that they gimbal with the electric thrusters so that transfer of control can be effected whenever necessary.

The orbit transfer system shall be designed so that it can be installed on the SPS module piecemeal as dictated by cargo launch vehicle payload mass and packaging limitations. The system shall be designed for an in-space final mission readiness checkout, with automated onboard status monitoring and built-in test with diagnostic software.

The orbit transfer system will consist of two or more physically separate installations on an SPS module, with installation location details dependent on the SPS module design. The OTS shall be designed such that one OTS installation can be configured as master unit for flight control purposes and that the other OTS units on the same module can be slaved to it. Communications between OTS units shall not require dedicated wire or cable connections between units. The OTS shall be capable of autonomous navigation, guidance, and control on the nominal mission profile. Each OTS shall be capable of accepting by suitable communication links, override commands to modify the thrusting program, e.g.; for collision avoidance, as well as remote piloting commands for terminal rendezvous prior to docking operations.

Rationale

The propellant restriction results from the large quantities required for an SPS program. Typical quantities are 20,000 to 40,000 tons of electric propellant per SPS. World reserves of scarce resources such as mercury or cesium are inadequate.

Attitude control studies (see Vol. V) have conclusively shown that attitude control is required during passages through the Earth's shadow. Without such control, the satellite module will be severely misoriented upon emergence from the shadow and will not be able to resume power generation. The remaining requirements derive from the way in which the OTS modules are to be used. This information may be found in Volume V.

5.1.3 SPS Interfaces

Requirement

The orbit transfer system shall be designed with the SPS modules in such a way as to minimize the total SPS cost attributable to the SPS and the OTS installation. Present estimates of specific requirements in this area are as follows:

Structure

The OTS structure shall be designed to attach to the SPS module structure such that thrusting loads are adequately distributed into the SPS structure and such that the OTS can be removed from the SPS module when necessary to accommodate joining the modules together to form the complete SPS.

Electrical

The OTS shall accept unregulated SPS module power at the SPS - OTS interface. The power will be supplied at a voltage that minimize the SPS scar associated with providing OTS power. The OTS shall provide all required power processing and control.

Fluids

There shall be no fluid interfaces, except in the case where commonality of propellant storage between OTS requirements and SPS on-orbit propulsion may be cost effective.

Avionics

Avionics interface requirements are TBD, but shall be minimized. The OTS shall provide all guidance, navigation, control, communications, and data management capability needed for the orbit transfer.

Mechanical

The OTS shall provide all thrust vector gimbals and gimbal actuations.

Thermal

The OTS shall provide all of its own thermal control needs. The OTS thermal control system shall not induce deleterious thermal control environments on the SPS.

Rationale

These requirements are provisional. They represent current estimates of interfacing conditions that will minimize costs.

5.2 PERFORMANCE

5.2.1 Criteria

Requirement

The payload mass delivery requirement shall be stated as the mass of the applicable SPS module with scar provisions included such as OTS-dedicated power distribution and any SPS oversizing to compensate for transfer degradation. The assembled SPS modules may be used to transport additional items, e.g., antenna parts or SPS maintenance spares. These items shall be identified and included in the payload mass capability.

All SPS-associated costs incurred as a result of the transportation mode shall be accounted as transportation costs.

Flight performance propellant reserves shall be 2% of the total equivalent delta v requirement (the delta v that would result if all propulsion were applied to translation), and shall be apportioned between chemical and electric propellant in accordance with the nominal mass proportion of each. The total equivalent delta v requirement shall be established based on six-degree-of-freedom numerical simulation of the orbit transfer, accounting for propulsion requirements for gravity gradient

effects and vector losses resulting from plume impingement restrictions on gimbal angle. Chemical propulsion shall be used for attitude control during shadow periods. If a suitable simulation is not used to compute the total equivalent delta v requirement, it shall be assumed to be 10% greater than the point-mass value.

Rationale
Self-explanatory.

5.2.2 Payload Mass Capability

Requirement
A definitive payload mass value cannot be specified, since it depends on the SPS mass and the number of modules into which the SPS is divided. A representative range is 10,000 to 15,000 metric tons per module.

Rationale
The representative range is about 1/8 of the total mass of an SPS.

5.2.3 Payload Volume

Requirement
The OTS shall place no limitations on payload volume. The moment of inertia unbalance of the SPS modules, with the OTS and any additional transported mass installed, shall remain within the attitude control capability of the OTS for all flight conditions to be experienced during the orbit transfer. This may influence the selection of SPS module size and shape and the OTS installation configuration.

Rationale
This requirement allows the SPS module to always be controllable during the transfer.

5.2.4 Mission Timeline and Delta V Budget

Requirement
The ideal point-mass delta v from the construction orbit at 478 km, 31°, to geosynchronous orbit at 0° inclination, is approximately 5920 m/sec. Under the 10% rule for control and the 2% reserve rule (see 5.2.1 above), the total required delta v capability is 6642 m/sec. This includes electric and chemical propellant. Since the electric and chemical thrusting is intermixed, the effective Isp can be roughly estimated as

$$I_{eff} = \frac{1}{\frac{0.1}{I_{chem}} + \frac{0.9}{I_{elec}}}$$

Orbit transfer simulations shall be used as available to refine the estimates of delta v and propellant required. Final design requirements shall be based on detailed six-degree-of-freedom simulations.

The mission timeline, e.g., trip time, shall be a cost-optimal selection, constrained by controllability. The cost-optimal trip time is estimated as 200 days. (This trip time provides sufficient thrust for controllability in the cases that have been investigated . . . refer to volume V).

Rationale

These representative delta V requirements were developed under the Future Space Transportation Systems Analysis Study. A comprehensive discussion of low-thrust flight performance applicable to SPS orbit transfer is beyond the scope of this document, but may be found in the final report for the above study, Volume 3.

5.2.5 Propellant Tank Capacity

Requirement

Propellant tanks on the OTS shall be sized to accept the required propellant loading for any orbit transfer departure condition, e.g. any time of year and any orientation of the construction orbit line of nodes.

Rationale

The total propellant load and the fraction that is chemical propellant vary somewhat as a function of departure season and construction orbit orientation. The OTS hardware should be designed to accommodate any actual departure situation. A more complete discussion of departure time factors is given in the Future Space Transportation System Analysis study final reports.

5.2.6 Departure Timing

Requirement

The OTS design shall support the achievement of actual departure (initiation of orbit transfer) within ± one day of scheduled departure. The OTS design shall accommodate the performance requirements of any departure schedule that may be selected.

Rationale

There are periods, due to the changing departure geometry (change of season and construction orbit nodal regression), when the rate of increase of required propellant load exceeds nominal delivery rates. If a departure schedule during one of these periods is slid beyond the makeup capability of performance margins, the departure may be delayed for several weeks. This would seriously disrupt overall operations.

5.2.7 Reliability and Design Life

Requirement
Mission design life for OTS hardware shall be 8000 hours. Hardware which is to be reused shall be designed for 8000 hours per mission with refurbishment between missions as appropriate to minimum cost.

Probability of nominal mission completion shall be 0.95, considering failure modes of the OTS but not the SPS module. Probability of successful abort from an aborted nominal mission shall be 0.95. (The abort mode shall be coplanar transfer to an orbit of at least 20,000 km altitude).

Rationale
The nominal mission duration is 4800 hours. The design life provides margin for extending the nominal duration and for additional margin between mission duration and design life.

Reliability requirements are preliminary estimates. The abort mode provides attainment of a sufficient altitude that crew involvement in maintenance and repair would not result in excessive van Allen radiation exposure.

5.2.8 Built-In Test and Status Monitoring

Requirement
Each OTS installation shall provide built-in test and status monitoring capability. The master OTS shall collect, process and format these data for display and communication. Initial operations shall provide direct communications of all data; this shall evolve as rapidly as is practicable to communication only of out-of-specification conditions and software-processed diagnostics.

Rationale
This requirement is intended to simplify checkouts and minimize mission control requirements.

5.3 SUBSYSTEMS REQUIREMENTS

5.3.1 Structures

5.3.1.1 Framework Structures

Requirements
The OTS modules shall include a structural system that accommodates OTS hardware installations on the SPS modules. The OTS structure shall not duplicate SPS structure and shall be designed for convenient removal as appropriate to paragraph 5.1.3. The OTS structure shall transmit and

distribute OTS thrust loads to the SPS module. The maximum design load shall be the combined electric and chemical thrust capability of the OTS (nominally 2x electric thrust). A combined structures analysis, considering the OTS and the SPS modules, shall be performed to substantiate structural integrity and compatibility.

Rationale

These requirements are consistent with the overall requirement on the OTS to serve as a temporary subsystem that converts an SPS module into a powered spacecraft.

5.3.1.2 Main Propellant Tanks

Requirement

Propellant tanks shall be of welded construction, fabricated from a metal alloy compatible with the propellants to be contained. Tanks shall be free-standing (not requiring internal pressure) under any loading conditions. Tanks shall be membrane-loaded by internal pressure. Tanks shall be designed for launch to low earth orbit loaded with propellant. Maximum acceleration will depend on launch vehicle characteristics; a nominal value of 5 g's shall be used if detailed characteristics data are not available. Propellant tanks shall be designed such that all welds are visually inspectable from at least one side and such that all welds are radiologically inspectable.

Design working pressures for electric propellant tanks shall be 150 kpa and for chemical propellant tanks, 1000 kpa. Design life at pressure shall be 8000 hours.

Rationale

Standard design practice: the working pressures are sufficient to feed propellants to thrusters without pumping. The design life corresponds to OTS design life.

5.3.2 Propulsion

5.3.2.1 Electric Thrusters

Requirement

Electric thrusters may be of the electrostatic ion or magnetoplasmadynamic (MPD) type. Electric thrusters shall be designed to utilize electric propellant fed in vapor form from the propellant feed system.

Performance requirements for electric thrusters are not well defined. The following represents best estimates available.

Ion thrusters shall be sized in the 100-150 cm diameter range. Power handling capability shall be maximized for the specific impulse selected within the limits imposed by design life requirements. MPD thrusters shall be at least 500 kw_e each and not more than 5000 kw_e each. Physical size of MPD thrusters is TBD.

The specific impulse range of primary interest is 3000 to 7000 seconds. The value to be selected within this range will depend on thruster characteristics. Ion thrusters tend to optimize in the 5000-7000 second range; MPD thrusters may be constrained by life considerations to less than 5000 sec.

Thruster efficiency shall be maximized subject to Isp selection and life requirements. Thruster life shall be 8000 hours with 1000 starts. Starting time for the thrusters shall not exceed 10 minutes.

Rationale
These provisional requirements are based on results of electric orbit transfer systems studies reported in Volume 5.

5.3.2.2 Electric Power Processors

Requirement
Power processor requirements depend on thruster selection. Power processors may be of the rotating machine or solid state type, or a combination thereof. Power processors shall be designed to accept raw power supplied from the SPS module at a voltage selected to minimize module penalties, e.g. for conductor mass, and provide processed power and power control to the thrusters according to their requirements. Typical ion thruster requirements are discussed in Volume 5. The power processors shall include thruster arc suppression capability and shall be designed to accept the power characteristics fluctuations that arise from SPS module operation. Power processors shall include passive or active thermal control as required to maintain their operating temperature within safe limits. Power processors shall be designed to mount on the thruster panels, except for the thermal control radiators. The latter may require installation on the OTS fixed structure.

Rationale
These provisional requirements are based on the SPS electric orbit transfer systems studies reported in Volume 5.

5.3.2.3 Chemical Thrusters

Requirements
Chemical thrusters shall be designed to use oxygen/hydrogen propellants provided in vapor form at tank pressure ($\approx$ 1000 kpa). Thrust level is TBD but will be on the order of 1000 N. Propellant

conditioning requirements are TBD. Thrusters shall be designed for pulsed or continuous mode operation and shall be designed for installation on the electric thruster panels. Thrusters shall include valves required for propellant flow control and shall employ catalyst or spark ignition. Thruster life shall be 1000 hours steady-state with 1000 starts plus 100 hours pulse-mode operation. Pulse length is TBD.

Rationale
These provisional requirements are based on the SPS orbit transfer system studies reported in Volume 5. The relatively shorter chemical thruster life requirement reflects its use only during shadow periods.

5.3.2.4 Propellant Feed Systems

Requirement
The propellants shall be thermally expelled from the tanks by an optimized combination of heat leak and internal heaters. Propellant feed lines shall be all-welded and shall cross the gimbal joint through suitable flexible wraparounds such that dynamic seals are not required. Accumulator capacity on the thruster panels shall be sufficient to prevent excessive pressure oscillations due to starts and stops of propellant flow.

Rationale
For high specific impulse systems, the mass penalties associated with thermal expulsion are not prohibitive. Reliability will be enhanced by this semi-passive approach.

5.3.3 Electrical Power Subsystem
(Electric thruster power processing and distribution is considered to be part of the propulsion system.)

Requirement
The electrical power subsystem shall provide storage, distribution and processing for the OTS chemical propulsion and data and communications subsystems. During normal operation, raw power for this function shall be tapped from main propulsion electrical busses at the input to propulsion power processors. The electrical power subsystem shall provide sufficient storage to operate the chemical propulsion, data and cummunications subsystems normally for two hours, plus an emergency reserve (critical functions only) for 12 hours. Propellant expulsion heaters need not be operated from storage; tanks can be operated on blowdown for occultation periods.

Rationale
These functional requirements are preliminary estimates only.

5.3.4 Avionics

Note: Refer also to Paragraph 5.1.2, "Operational Characteristics."

5.3.4.1 Guidance, Navigation and Control

Requirements

The GN&C system shall be resident in the "master" OTS module. The GN&C system shall provide autonomous control of the OTS through all elements of the nominal mission profile excepting terminal rendezvous and docking with other SPS modules. The GN&C systems shall provide for remote piloting override for these latter functions and may include automated terminal rendezvous and docking with suitable cooperative target systems.

The GN&C system shall provide automated mission planning and targeting to accommodate the variations in the nominal mission profile that result from variations in low Earth orbit altitude, inclination and line of node, and variations in the target longitude in geosynchronous orbit.

The GN&C system shall provide collision avoidance thrust program modifications based on externally-supplied collision threat state vector data. The GN&C system shall use an appropriate combination of stellar-inertial, externally-communicated and cooperative target references.

Rationale

These are basically functional requirements. Autonomous capability is needed to minimize tracking and mission control requirements. Automated mission planning and targeting is highly desirable to simplify operations. Collision avoidance capability is essential to minimize requirements for repair to SPS modules.

5.3.4.2 Communications Subsystem

Requirement

The communications subsystem shall provide for tracking, command and control through external sources by suitable RF links. Communications capability shall exist in the master OTS module for communicating with ground stations either direct or through TDRSS, and with orbital operations bases in low Earth orbit and geosynchronous orbit. The use of steerable antennas to enhance communications shall be avoided to the extent practicable.

During developmental and early operational phases, full telemetry of all OTS vehicle and SPS module data shall be provided. In the mature operational phase, telemetry will be confined to positional (state vector) data and out-of-specification conditions.

Inter-OTS module communications shall be provided by communications elements installed on each module.

Rationale

These are functional requirements. The objective is to evolve to maximum reliance on onboard data recording and identification of problems requiring attention by onboard diagnostic software.

5.3.4.3 Data Management Subsystem

Requirement

The data management subsystem shall provide all onboard data acquisition, collection, distribution, formatting, processing and disposition (including onboard recording). The data management system, when mature, shall provide (1) onboard recording of all vehicle and subsystems performance and diagnostic data, (2) for cases where OTS hardware is to be reused, onboard recording of a summary anomaly and diagnostic data set for maintenance attention, and (3) realtime telemetry of caution and warning data including onboard software-processed diagnostics for any condition that may lead to abnormal termination of the missions or hazards to flight crew or construction base personnel or facilities. During all development and operational phases, the data management subsystem, interfacing with the communications subsystem, shall provide a highly reliable and secure command override link, capable of meeting all range safety and other safety requirements. This override link shall also provide for remote piloting of docking maneuvers at the LEO and GEO construction bases.

The data management subsystem shall also provide for automated monitoring of OTS condition and automated built-in test prior to initiation of major mission events.

It is a design objective to use advanced processor and memory technology with high level languages to the degree possible.

Rationale

These requirements are intended to facilitate airline-type operations. The automated diagnostics are intended as a substitute for flight crew "squawks" which are the primary indicator of maintenance needs in manned aircraft.

5.3.5 Thermal Control Subsystem

Each OTS subsystem shall provide its own thermal control.